IRRIGATION INSIGHTS

NO.1

SOIL WATER MONITORING

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Acknowledgments

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1. Introduction

Irrigators are under increasing pressure to manage water more prudently and more efficiently. This pressure is driven by product quality requirements, economic factors, demands on labour and the desire to minimise the resource degradation and yield loss that can result from inefficient irrigation. The need for farmers to irrigate more efficiently has led to an explosion in the range of equipment available for measuring soil water status.

The key to efficient on-farm irrigation water management is a good knowledge of both the amount of water in the soil profile that is available to the crop and the amount of water the crop needs. Measuring and monitoring soil water status should be essential parts of an integrated management program that will help you avoid the economic losses and effects that under irrigation and over irrigation can have on crop yield and quality. They will also help you to avoid the environmentally costly effects of overirrigation: wasted water and energy, leaching of nutrients or agricultural chemicals into groundwater supplies, and degradation of surface waters with contaminated irrigation water runoff.

No existing resource offers a comprehensive, one-stop guide to all the available soil water sensing and monitoring equipment. Irrigation extension staff, consultants, equipment sales people and irrigation managers face a huge task in finding out about the range of technology available and becoming familiar with the features, advantages and limitations of each system. By having the information at their fingertips they can more easily match the equipment to the required task and budget.

This *Irrigation Insights* information package brings together information on current equipment and techniques for measuring and monitoring soil water status, extending to their use as controllers in automatic irrigation systems. We have limited the equipment described here to those products with agents and backup within Australia. The hub of the publication is a collection of tables summarising the main product features. This enables you to compare product features. As well as technical data, there is also commercial information on suppliers, contact details, availability and price (accurate at August, 2000). Case studies from personal experience and from the literature provide further insight into the advantages and limitations of each device in relation to its potential applications.

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2. Measures of soil water status

Gravimetric, volumetric and potential measures

GRAVIMETRIC, VOLUMETRIC AND POTENTIAL MEASURES

There are three common ways to describe the wetness of soil: *gravimetric* soil water content (SWC), *volumetric* SWC, and soil water *potential*. Which description is used depends partly on how the information will be used. You can use all three methods for the same purpose, i.e. to work out whether you need to irrigate.

Gravimetric SWC refers to how much water is in the soil on a weight basis, for example, 0.3 g water per 1 g of dry soil. This is the easiest way to measure SWC. All you do is take a small soil sample, weigh it, dry it in an oven for a day, and then weigh it again. The weight difference is the water extracted from the sample.

One problem with gravimetric measurement is that the densities of different soils vary so a unit weight of soil may occupy a different volume. To allow you to compare the water contents of different soils and to calculate how much water to add to the soil to satisfy a plant's requirement, you need to do a *volumetric* measurement.

Volumetric SWC is the most popular method of reporting the moisture status of soil. It is calculated by multiplying the gravimetric SWC by the soil *bulk density*, and it uses units of cubic centimetres (or millilitres) of water per cubic centimetre of soil. The bulk density is the mass of soil solids per unit volume. The bulk density is also used to calculate how much water a soil can hold.

Volumetric measurements are convenient for measuring how full the soil is, but they give no indication of how difficult the water is to remove. As the soil becomes drier, the water is held more tightly and more energy is needed to extract it. The soil water *potential* is a measure of this tension and is expressed in kilopascals (kPa). Potential is also referred to as soil water *suction.* This is the term used in the package. Irrigation can be managed to maintain soil water suction within the correct range so that the crop is not stressed. However, trial and error are needed to determine the volume of water to be added.

As an introduction to these measurements, Table 1 shows the average values for a range of soil textures.

Table 1

TABLE 1

Representative gravimetric (g/g) and volumetric (cm^3/cm^3) soil water content and soil water suction values (kPa).

	Sand Bulk density = 1.65 g/cm^3			Loam Bulk density = 1.55 g/cm^3			Clay Bulk density = 1.3 g/cm^3		
	G	**V**	**S**	**G**	**V**	**S**	**G**	**V**	**S**
Saturation	0.23	0.38	0	0.27	0.42	0	0.38	0.5	0
Field capacity	0.10	0.17	33	0.24	0.37	33	0.33	0.43	33
Wilting point	0.07	0.12	1500	0.15	0.23	1500	0.25	0.33	1500

(G)ravimetric, (V)olumetric, (S)uction.

Water depth

WATER DEPTH

Most irrigators refer to water applied to a crop in volumetric terms, for example, in megalitres per hectare (ML/ha) or Dethridge wheel revs (rpm).

Application rates can also be expressed in terms of depth, for example, millimetres. A water depth is merely a volume averaged over a land area. For instance, 1 ML

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applied over 1 ha is equivalent to 100 mm. This allows comparison with factors such as rainfall and crop water use or evapotranspiration. For example, as an aid to irrigators in the Murrumbidgee Irrigation Area, NSW, the potential crop evapotranspiration (in mm) is included in the nightly weather report. Using a simple calculation, this figure can be converted to a volume to be applied to the crop.

Variability

Soil type, crop density, disease, application uniformity, time of season - all cause variation the irrigator must deal with.

INSTALLATION IS CRITICAL!

For best results, it is important that the instrument is placed in the average soil type, next to the average plant, at the depth of average water uptake and in the zone of average water application.

VARIABILITY

Agriculturalists are very aware of the variability that exists in their systems. In fact, they put a lot of effort into trying to even out this variability and get a uniform product. Subtle and sharp changes in soil type are evident both across the paddock and down the profile. Variations in crop growth can point to soil changes, past paddock use, disease, or irrigation application problems such as blocked drippers. Even very close to a plant there will be variations in where the plant extracts its water from. Time brings in another level of variability, with differences throughout the day and season in where and how much water is being extracted from the soil. Consider, for example, a row of drip-irrigated grapevines. Not only is there soil variation to contend with, but also variation in the amount of water applied between the drip emitters: from very wet at the emitter to drier in between. Impose on this a row of plants that alter where the irrigation water spreads, and you can see that the system is quite complex.

All the available soil-water-measuring instruments can tell us the soil water status at a particular point in a paddock. If you have a number of sensors, then you can place an array throughout the profile to give more information. However, because there are practical limitations in the wiring or in the time taken to read them, you will generally have to place them close together. Depending on the soil-water-monitoring system there may be only a single reading every few hectares. This reading has to average out all the variability present in the whole area. That is, you are assuming that the instrument is placed in the average soil type, next to the average plant, at the depth of average water uptake and in the zone of average water application. You then design an irrigation schedule to satisfy the plant and soil in this position. Even if there are enough sensors present to show the variation in the field, how do you respond to the variations? Do you water to satisfy the driest part of the field, ensuring no plant is underwatered? Or do you water to the wettest instruments, thus using water very efficiently but at the risk of decreased yield?

All these issues must be taken into account when you are designing a soil-water-monitoring system. We strongly recommend that you talk to someone experienced in these matters, such as a consultant or irrigation officer, before you go ahead.

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3. Technologies for measuring soil water status

In this package we use the following definition of a soil water sensor:

A soil water sensor is an instrument which, when placed in a soil for a period of time, provides information related to the soil water status of that soil (Cape 1997).

Gravimetry (in this case drying soil samples and then weighing them) is the only *direct* way to determine how much water is in the soil. All other techniques rely on *indirect* methods that measure other properties of the soil that vary with water content. The 24 products listed in this section all exploit one of the following indirect measurement systems for measuring the soil moisture status:

a) suction
   • porous media instruments
   • wetting-front detectors

b) volumetric water content
   • soil dielectric: time domain reflectometry, frequency domain reflectometry (FDR or capacitance)
   • neutron moderation
   • heat dissipation.

The basic concepts behind each of these are as follows.

Porous media

POROUS MEDIA

Porous media instruments are made from materials that are porous to water, that is, materials through which water can move and be stored in the pores. Water is drawn out of the porous medium in a dry soil, and from the soil into the medium in a wet soil.

Porous media instruments measure soil water potential and take three forms:

> tensiometers
> resistance blocks
> combination volumetric SWC – porous material devices.

The range of measurements that can be achieved with these types of devices is shown in Figure 3.1.

Tensiometers

A tensiometer is an instrument that directly measures soil moisture potential. It consists of a porous ceramic tip, a sealed water-filled plastic tube and a vacuum gauge (Goodwin 1995). The porous cup is buried in the soil and allows water to move freely between the water-filled tensiometer and the soil. As the soil around the cup dries, the potential increases, and water moves out of the tensiometer until the potential within the tensiometer is the same as that of the soil water.

Since the tensiometer is an airtight device (Figure 7.1), as water moves out from the porous cup a negative pressure (a vacuum or suction) equivalent to the soil potential is created in the tensiometer. If the soil around the tensiometer becomes wetter (for example, from rain or irrigation) the soil potential decreases, and soil water flows through the porous walls of the cup into the tensiometer, decreasing the suction.

The soil suction reading relates directly to the amount of energy a plant must use to remove water from the soil, and hence is a more meaningful measure of plant stress than the soil water content. The suction is measured with a vacuum gauge or pressure transducer. The transducer can either be a handheld device (used to read many ten-

siometers manually) or be permanently installed in the tensiometer and connected to a logger. The portable device has a hollow needle that is inserted through a rubber bung or septum to measure the vacuum.

Tensiometers cannot be used to measure soil water suction greater than 75 kPa. Suctions above this cause the vacuum in the tensiometer to break down, as air enters the ceramic tip. They are fine for most annual vegetable crops, orchards, nuts and pastures, but they are not adequate for the controlled stressing of plants such as grapevines, where suctions as high as 200 kPa are recommended to produce good wine quality.

Resistance blocks

Resistance blocks consist of two electrodes embedded in a block of porous material that is buried in the soil. As with tensiometers, water is drawn into the block from a wet soil and out of the block from a dry soil. The electrical resistance of the block is proportional to its water content, which is related to the soil water potential of the surrounding soil.

Combination devices

Several of the soil water suction sensors consist of volumetric SWC sensors embedded in porous materials with known water-retention properties. The water content of the material equilibrates with the suction of the surrounding soil and is measured by the sensor.

Figure 3.1

FIGURE 3.1 Measurement ranges for several soil-water-tension monitoring instruments.
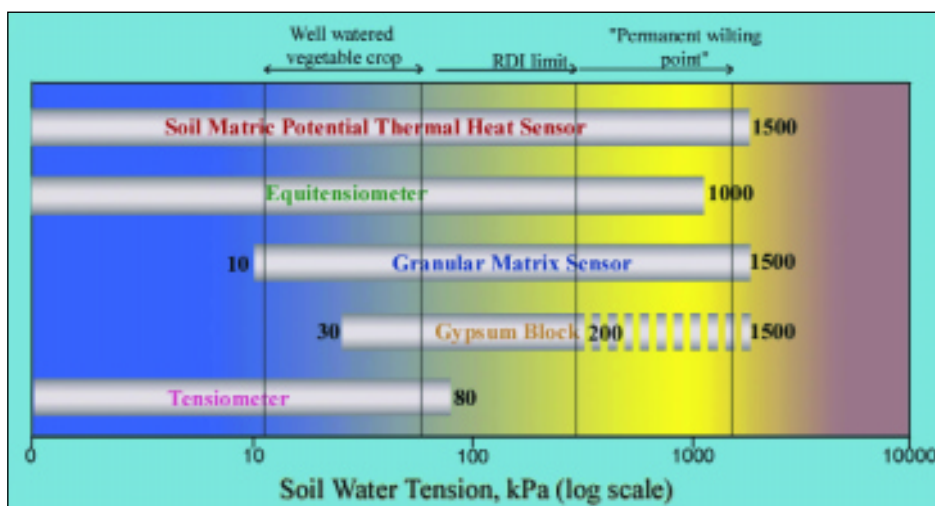
Key points:
> Tensiometers are suited to vegetable crops, orchards, nuts and pasture.
> Gypsum blocks and granular matrix sensors are suited to Regulated Deficit Irrigation (stone fruit and wine grapes).
> Thermal heat sensors and equitensiometers cover the whole range and are best suited for research work.

Wetting-front detectors

WETTING-FRONT DETECTORS

(by Dr Paul Hutchinson, CSIRO Land and Water, Griffith, NSW)
Wetting-front detectors are soil moisture switches that are buried at the locations of interest. When soil moisture increases above a set point the detector switches on.

When the soil dries to below the set point the detector switches off. Wetting-front detectors are cheap because they do not need to have continuous outputs that are calibrated to the soil water content.

Wetting-front detectors provide useful information to irrigators in three main ways:

Warning signals
If a wetting-front detector is placed near the bottom of the root zone it can act as a warning signal that overirrigation is occurring. Irrigation beyond this depth is wasted, because the crop cannot get access to this water. Irrigators can use a wetting-front detector to reduce overirrigation, fertiliser loss and waterlogging and, as a consequence, to increase crop yield.

Regulation of amount of water irrigated
Wetting-front detectors can be used to regulate the amount of irrigation to the crop's water demand by placing the detector within the root zone and turning off the irrigation when the wetting front is detected. This regulation occurs because the wetting-front speed depends on how dry the soil is before irrigation. If the soil is relatively dry, the wetting front moves slowly into the soil. This occurs because the soil absorbs much of the water and hence slows the progress of the wetting front. Conversely, if the soil is already wet, the wetting front moves fast because the irrigation water finds little available space to occupy.

Collection of soil-water samples
Wetting-front detectors can be designed to collect samples of soil water from the wetting front. These samples contain solutes such as salt and nitrate. When analysed, these samples can provide useful information about managing fertilisers and the leaching of salt from the root zone (Stirzaker and Hutchinson 1999).

Soil dielectric

SOIL DIELECTRIC
The dielectric constant is a measure of the capacity of a non-conducting material to transmit electromagnetic waves or pulses. The dielectric of dry soil is much lower than that of water, and small changes in the quantity of free water in the soil have large effects on the electromagnetic properties of the soil water media.

Two approaches have been developed for measuring the dielectric constant of the soil water media and, through calibration, the SWC: time domain reflectometry and frequency domain reflectometry.

Time domain reflectometry
The speed of an electromagnetic signal passing through a material varies with the dielectric of the material. Time domain reflectometry (TDR) instruments (for example, TRASE/Tektronix) send a signal down steel probes (called wave guides) buried in the soil. The signal reaches the end of the probes and is reflected back to the TDR control unit. The time taken for the signal to return varies with the soil dielectric, which is related to the water content of the soil surrounding the probe.

TDR instruments give the most robust SWC data, with little need for recalibration between different soil types. However, they are extremely expensive and you may need additional electronic equipment to run them.

Frequency domain reflectometry
Frequency domain reflectometry (FDR) measures the soil dielectric by placing the soil (in effect) between two electrical plates to form a capacitor. Hence 'capacitance' is the term commonly used to describe what these instruments measure. When a voltage

is applied to the electric plates a frequency can be measured. This frequency varies with the soil dielectric.

FDR-type products have been the main area of expansion in the production of soil-water-monitoring equipment.

All dielectric sensing products have a relatively small measurement sphere of about 10 cm radius, with 95% of the sphere of influence within 5 cm. This makes them sensitive to inconsistencies introduced during installation, such as air gaps beside access tubes. The Aquaflex®, developed in New Zealand, seeks to integrate such problems over a large soil volume by making the single sensor very long (about 3 m).

Within this product group a variety of installation methods are represented, including by access tube, portable sensors and buried sensors. The Gopher® (see later) is operated similarly to a neutron probe. One sensor is lowered down an access tube to the required depth. It can then be moved to another location. EnviroSCAN® also uses an access tube, but it consists of an array of identical sensors placed permanently at set depths, offering the advantage of both time and depth series logging.

To calibrate dielectric sensors, two-point (wet and dry) gravimetric sampling is used. EnviroSCAN is provided with a 'universal calibration', but there is also a comprehensive calibration procedure that can be used if you need greater accuracy.

For more technical explanations of TDR and FDR see *Appendix 2 and Appendix 3*.

Neutron moderation

NEUTRON MODERATION

The neutron moisture meter (NMM) was the first device used to measure SWC in the 1950s. In Australia, it became popular in the 1970s and 1980s and was the instrument of choice for irrigation scheduling consultants. Most irrigation areas still have neutron probe services, but the development of newer electronic equipment with less emphasis on human input, as well as the problem of the nuclear stigma, have meant their use is decreasing.

The neutron moderation technique is based on measuring fast-moving neutrons that are slowed (thermalised) by an elastic collision with existing hydrogen particles in the soil. Hydrogen is present in the soil as a constituent of soil organic matter, soil clay minerals and water. Water is the only form of hydrogen that will change from measurement to measurement. Therefore, any change in the counts recorded by the NMM is due to a change in the water, with an increase in counts relating to an increase in soil water content.

For a more technical explanation of the NMM see *Appendix 4*.

Heat dissipation

HEAT DISSIPATION

Heat capacity is the amount of heat energy needed to increase the temperature of a quantity of water by 1ºC. Sensors in this category exploit the fact that water has a far greater heat capacity than soil.

Therefore, if a wet soil and a dry soil are subjected to an equivalent amount of heat energy, the wet soil will experience a lower increase in temperature. Sensors using this principle consist of a heat source separated by a known distance (3 to 10 mm) from a temperature sensor. They are buried at the depth of choice. A burst of heat energy of known amount is emitted from the heat source. As the heater is turned off, the temperature sensor records the peak temperature increase for about one minute. The heat input and peak temperature change are then used to calculate the volumetric water content. Sensors are calibrated by measuring the bulk density and heat capacity of the soil into which they are placed.

These probes have a small measurement sphere (about 1 cm diameter), making them useful for high-resolution spatial-data gathering where many probes can be placed in a small area. Heat dissipation probes require sophisticated loggers to measure the temperature and power variables and to control the measurement timing. This also makes them well suited for time-series measurement.

4. Selecting a product

4. Selecting a product

The products discussed in this publication are described by the following 19 attributes:

1. Reading range	8. Country of origin	15. Irrigation system suited to
2. Stated accuracy	9. Remote access	16. Best soil type
3. Measurement sphere	10. Link to other equipment	17. Application
4. Output reading	11. Interface to PC	18. Capital cost
5. Installation method	12. Affected by salinity	19. Annual operating cost
6. Logging capability	13. Expansion potential	
7. Power source	14. Technical support	

When you are selecting a product, choose the attributes most important to you from the above list and compare them for each product. However, the dominant factor in the selection process will not be physical/plant/soil based, but will invariably be the trade-off between your initial capital investment and your ongoing labour cost. For example, a tensiometer is relatively inexpensive but must be read daily and maintained weekly. A modern multi-depth logging system is relatively expensive, but data can be sent straight to the office PC and viewed with little labour input. A further intangible consideration is that it needs great discipline to maintain a regime of manual readings.

To this end, an economic analysis of soil-moisture-monitoring equipment has been included in *Appendix 6* to demonstrate that the lifetime cost of a product should be included in the selection process.

Also included, as *Appendix 5*, is an example of a proforma for product selection that incorporates both important attributes and economic aspects.

Accuracy of equipment

ACCURACY OF EQUIPMENT

The most contentious equipment description is 'accuracy'. Accuracy can be stated in many ways:

> ability to reproduce actual soil water status (from oven-dried samples) in laboratory-controlled conditions with and without specific calibration
> ability to reproduce actual soil water status (from oven-dried samples) in field conditions with and without specific calibration
> repeatability: the degree of variation in consecutive readings taken over a short time interval
> resolution: the number of significant figures to which a measurement can be read, for example, an 8-bit device gives a resolution of 100 units/256 data steps = 0.4% resolution.

The relevant measurement will depend on how the equipment will be used. For instance, an irrigator applying water to relative set points may be interested only in a sensor with a high repeatability.

As there is no universal, objective source of measured accuracy available, we have used the manufacturers' 'stated accuracy' in this package.

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5. Summary table of product features

Table 5.1 describes the level of skill required for instrument operation.
  This objective score reflects the author's opinion and is split into three levels :

✔   Minimal skill - with a small amount of training a person is well able to accomplish the task.

✔✔   Considerable - a large investment is required to become proficient. The inference is that it may be more efficient to hire a consultant.

✔✔✔ Specialist - either specialised equipment or a high degree of theoretical knowledge is required.

Table 5.1

TABLE 5.1 Skill levels needed to operate different products

Products	Installation design	Installation	Calibration	Maintenance	Data retrieval	Data interpretation
				Skill required		
Aquaflex	✔	✔	✔PC/✔✔new	✔	✔	✔
Aquasensor	✔✔	✔✔	✔✔	✔	✔	✔
Aquaterr	✔	✔	Not required	✔	✔	✔
Buddy	✔✔	✔✔	✔	✔	✔	✔ / ✔✔
C-Probe®/Adcon	✔✔	✔✔	✔✔	✔✔	✔✔	✔ / ✔✔
Cut-off Sensor	✔	✔✔	Not required	Not required	No data collected	
Diviner 2000®	✔✔	✔	✔	✔✔	✔	✔
EnviroSCAN®	✔✔	✔✔	✔✔	✔✔✔	✔✔	✔ / ✔✔
Equitensiometer	✔	✔	Not able	Not required	✔	✔
FullStop	✔✔	✔	Not required	Not required	✔	✔
Gopher	✔	✔✔	✔	✔	✔	✔
Granular Matrix Sensors	✔	✔	Not required	Not required	✔	✔
Gro-Point	✔	✔	Not able	Not required	✔	✔
Gypsum Blocks	✔	✔	Not required	Not required	✔	✔
Moisture Activated Sprinkler System	✔	✔	✔	✔	No data collected	
Netafim Soil Moisture Data Collector	✔	✔	Not able	✔	✔	✔
Neutron Moisture Meter	✔✔	✔✔	✔✔	✔✔	✔✔	✔✔
Campbell 229	✔	✔	✔✔✔	Not required	✔✔	✔✔
Tensiometers	✔	✔	Not required	✔	✔	✔
ThetaProbe	✔/✔✔✔†	✔/✔✔✔†	✔✔✔	✔	✔/✔✔✔†	✔
TDR - Tektronix	✔/✔✔✔†	✔✔✔	✔✔✔	✔	✔/✔✔✔✔†	✔/✔✔✔✔†
TDR - TRASE	✔/✔✔✔†	✔/✔✔✔✔†	✔✔✔	✔	✔/✔✔✔✔†	✔/✔✔✔✔†
Campbell 615	✔	✔	✔✔✔	Not required	✔/✔✔✔✔†	✔
Wetting Depth Probe	✔	✔	Not able	Not required	✔✔✔	✔✔✔

† - when logged

Table 5.2

TABLE 5.2 Comparison of porous media technologies for measuring soil water tension.

	Tensiometer - meter read	Tensiometer - gauge read	Gypsum blocks irrigation system	Automatic matrix sensor	Granular thermal heat sensor	Soil matric potential	Equitensio-meter
Reading Range	0 to 80 kPa	0 to 80 kPa	30 to 1500 kPa	0-40% VWC	10 to 200 kPa	0 to -1500 kPa	0 to 1000 kPa
Stated Accuracy	~1 kPa	~ 1 kPa	~ 1 kPa	± 1% of user defined set point	~1 kPa	± 3 %	±5% (0 to 100 kPa) ±10 kPa (100kPa to 1000 kPa)
Measurement sphere	Up to 10 cm	Up to 10 cm	Up to 10 cm	~2 cm	Up to 10 cm	Up to 10 cm	2-3 cm diameter
Output reading	kPa from meter	kPa from gauge	kPa from meter	Resistance	kPa from meter	kPa from logger	Voltage calibrated to kPa
Installation method	Permanently inserted into augered hole	Permanently inserted into augered hole	Permanently inserted into augered hole	Permanently inserted into soil	Permanently inserted into augered hole	Permanently inserted into augered hole.	Buried
Logging capability	If fitted with transducer	If fitted with transducer	Yes	Future models	Yes	Yes	Yes
Power source	Meter - 9VDC	Nil	Meter - 5 V AC	24 VAC	Meter - 5 V AC	5 VDC from logger	5-15 DC
Country of origin	Australia	USA	Aust/UK/US	Australia	Aust/US	US	UK
Remote access	Subject to logger	Subject to logger	Subject to logger	Available	Subject to logger	Subject to logger	Subject to logger
Link to other equipment	Via logger	Via logger	Via logger	Links to solenoid	Via logger	Via logger	Via logger
Interface to PC	Meter download or Via logger	Via logger	Meter download or via logger	No	Meter download or via logger	Via logger	via logger
Affected by salinity	No	No	No effect < 6 dS/m (Soil solution)	Yes	No effect <6dS/m (Soil solution)	No	Not suitable for saline soils
Expansion potential	Via logger	Via logger	Via logger	6-way expansion unit	Via logger	Via logger	Via logger

Table 5.2
Continued

	Tensiometer - meter read	Tensiometer - gauge read	Gypsum blocks irrigation system	Automatic matrix sensor	Granular thermal heat sensor	Soil matric potential	Equitensio-meter
Technical support	Minimal	Minimal	Minimal	Low	Minimal	High	Minimal
Irrigation system suited to	All	All	All - esp. perennial/ Regulated Deficit.	Pressure	All	All	All
Best soil type	Light/Medium	Lighter	Heavier	Lighter soils	Medium/heavy	Medium/heavy	Heavier
Application	Irrigator/Research	Irrigator/Res.	Irrigator	Irrigator	Irrigator	Research/Irrigator	Research
Capital cost	$25 -most lengths (1) $16 -most lengths (2) $ 380-395 -Std Meter $ 795 - storage meter with software (SoilSpec) $4.35 Tensiometer tips (3)	$130 - $220 $200 - $250 - Service Kit	$15 - $30 $550 - reader	~ $300 $450 - expansion unit.	$ 65 - $90 $ 650 - $800 - reader	$ 145	$1300
Annual operating cost	~$2-3 $25 for 100 Tensiometer stoppers (Vaccutainer 6430) (4) $20 for 50 stoppers (1) Meter batteries	~$5 (new seals)	Battery for reader	Nil	Battery for reader	Nil	$395 every 2 years
Distributor	1) H & TS Electronics, (SoilSpec) 2). Terra Tech 3). Cooinda Ceramics (minimum order $200) 4). McFarlane Medical & Scientific Equipment	MEA, Selby Biolab, CSS MEA produces logging system.	MEA, CSA, Selby , Biolab	CLINCH	MEA, CSA, CSS	CSA	MEA
Reference page	18	20	21	22	23	24	25

Note: costs as at August 2000

Table 5.3

TABLE 5.3 Comparison of frequency domain reflectometry (capacitance) technologies for measuring SWC.

	EnviroSCAN®	Diviner2000®	C-Probe® Adcon	Gopher®	Buddy®	Aquaterr®	ThetaProbe®	Netafim data collector
Reading range	0-saturation	0-saturation	0-saturation	0-saturation	0-saturation	0-saturation	0-saturation	0-saturation
Stated accuracy	± 0.1 % when calibrated	± 0.5 % when calibrated	± 1 % when calibrated	± 1 % when calibrated	± 1 % when calibrated	Semi-quantitative	1% when calibrated, otherwise 5% m^3 m^{-3}.	± 4.5 %
Measurement sphere	10 cm radius (95% within 4 cm)	10 cm radius (95% within 4 cm)	Up to 10 cm (95% within 4 cm)	10 cm radius (95% within 4 cm)	10 cm radius (95% within 4 cm)	2-3 cm	2-3 cm	2-3 cm
Output reading	mm soil water	mm	0-100 units uncalibrated, or mm/% soil moisture calibrated	mm	mm	% (uncalibrated)	Voltage calibrated to m^3/m^3	30-80 soil moisture units
Installation method	PVC access tube	PVC access tube	PVC access tube	PVC access tube	PVC access tube	Pushed into soil	Hand inserted or buried at bottom of access tube	Buried in soil
Logging capability	Intrinsic	No	Intrinsic	No	Intrinsic	No	Yes	Intrinsic
Power source	12 V DC from solar cell	12 V DC internal rechargeable	6 V DC from solar cell	6 V DC 4 x AA	7.5 V DC	9 V DC (life ~1 year)	5-15 V DC	9 V DC (life ~1 year)
Country of origin	Australia	Australia	Australia/Austria	Australia	Australia	USA	UK	Israel
Remote access	Via range of add-on telemetry	No	Intrinsic radio telemetry	No	No	No	Via logger	No
Link to other equipment	No	No	Yes: weather sensors, flow rates, water table etc.	No	No	No	Via logger	No
Interface to PC	Mandatory	Yes, but not necessary	Mandatory	Yes	Yes	No	Via logger	Mandatory

Table 5.3

Continued

	EnviroSCAN®	Diviner2000®	C-Probe® Adcon	Gopher®	Buddy®	Aquaterr®	ThetaProbe®	Netafim data collector
Affected by salinity	Minimal	Minimal	Minimal	Minimal	Minimal	Minimal	< -0.0001 m^3/m^3 /mSm^{-1}	No
Expansion potential	Yes	No	Yes	No	Yes	No	Via logger	No (3 probes per logger)
Technical support	High: installation, interpretation and maintenance	Low: instructions available	High: installation, interpretation and maintenance	High: installation, interpretation	High: installation, interpretation	Minimal	Minimal if using included calibration	Minimal after initial setting
Irrigation system suited to	All permanent and annual	All permanent and annual	All: permanent plantings and row crops	All: permanent plantings	All: permanent plantings	Best for drip, especially buried drip	All	All
Best soil type	All	All	All	All	All	All	All	All
Application	Irrigator/research	Irrigator/research	Irrigator/research	Irrigator	Irrigator	Irrigator	Research/turf	Irrigator
Capital cost	From $3500	From $3500	Full pricing structure included in Appendix.	$1640	$1200 for 4 sensors $120 for extra sensor	$1250 (basic) $2185 (basic+soil) temp. and salinity	$630 (probe) $800-$850 (ThetaMeter®)	$800
Annual operating cost	$200-$600	Nil	$228 + maintenance @ $100 for first site, sliding-cost scale for multiple sites.	$200	$200	New battery	Nil	New battery
Distributor	Sentek	Sentek	Agrilink	Soil moisture technology	Soil moisture technology	Selby Biolab	MEA	Netafim Australia
Reference page	26	28	29	30	32	33	34	35

Note: costs as at August 2000

Table 5.4

TABLE 5.4 Comparison of time domain reflectometry (TDR) technologies for measuring SWC.

	Tektronix 1502	TRASE	Campbell Scientific TDR 100	Water Content Reflectometer (615)	Aquaflex®	Gro-Point®
Reading range	5%-50%	5%-50 %	5%-50%	0%-50%	0%-70%	8%-42% (standard) 5%-50% (extended)
Stated accuracy Measurement sphere	0.5%-1% in field ~3 cm radius around length of wave guides (< 0.8 L)	0.5%-1% in field ~3 cm radius around length of probes (< 0.8 L)	0.5%-1% in field. ~3 cm radius around length of probes (< 0.8 L)	± 2.5% ~3 cm radius around length of probes (< 0.8 L)	± 2% accuracy ~2.5 cm radius over a 3^m length (cylindrical volume of 6 L)	± 1% ~3 cm radius around length of probes (0.8-4 L)
Output reading	Nanoseconds calibrated to volumetric SWC	Nanoseconds calibrated to volumetric SWC	Nanoseconds calibrated to volumetric SWC	Frequency calibrated to volumetric SWC	Volumetric moisture content in %	Volumetric SWC
Installation method	Buried *in situ* or inserted for manual readings	Buried *in situ* or inserted for manual readings	Buried *in situ* or inserted for manual readings	Buried *in situ* or inserted for manual readings	Buried *in situ*	Buried *in situ* or inserted for manual readings
Logging capability	Via PC or logger	Logging available	Via logger	Via logger	Logging available.	Via logger
Power source	12 V DC external source	12 V DC internal rechargeable battery	5-8 V DC	12 VDC	Battery/solar/ mains power	5.5-18 V DC
Country of origin	US	US	US	US	NZ	US
Remote access	Via logger telemetry	Via telemetry	Via logger telemetry	Via logger telemetry	Via logger telemetry	Via logger telemetry
Link to other equipment	Via logger	Via logger	Via logger	Via logger	Via logger, or to other equipment with 4-20 mA or frequency/pulse outputversion of sensors*	Via logger
Interface to PC	Required	Yes	Via logger	Via logger	Via logger or PalmPilot	Via logger

Table 5.4
Continued

	Tektronix 1502	TRASE	Campbell Scientific TDR 100	Water Content Reflectometer (615)	Aquaflex®	Gro-Point®
Affected by salinity	Reduces signal return	Reduces signal return	Reduces signal return	> 2 dS/m needs recalibration	Sensor measurement adjusted for soil conductivity and soil temperature	At high levels
Expansion potential	Via multiplexing	Via multiplexing	Via multiplexing	Via multiplexing	See above*	Yes
Technical support	High	High	High	High	Low support required	Low
Irrigation system suited to	All	All	All	All	All	All
Best soil type	Difficulty in dense, salt or high clay soils	Difficulty in dense, salt or high clay soils	Difficulty in dense, salt or high clay soils	Difficulty in dense, salt or high clay soils	All	Difficulty in dense, salt or high clay soils
Application	Research	Research	Research	Research/irrigator	Irrigator/research	Irrigator
Capital cost	$15,000 + PC and software	$23,000 (portable system)	$7500-$8000	$400-$475 $400 (HydroSense® display)	$740 (sensors) $530 (handheld reader)	$400 (standard) $530 (extended)
Annual operating cost	Nil	Nil	Nil	Nil	Nil	Nil
Distributor	CSA	Selby Biolab	CSA	CSA	Streat Instruments Ltd (NZ) SMMS (Vic) WaterCorp (SA)	IIS
Reference page	37	38	39	40	41	42

Note: costs as at August 2000

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Table 5.5

TABLE 5.5 Features of the neutron moisture meter, AquaSensor, and wetting-front detectors.

	Neutron moisture meter	AquaSensor	FullStop	Wetting depth probe	Cut-off sensor
Reading range	0%-60%	Field capacity to 10% below field capacity	Switches at 2 kPa soil suction, resets at 1 kPa	Instrument measures on/off passage of wetting front	Instrument measures on/off passage of wetting front
Stated accuracy	± 0.5% when calibrated	± 1 %	-	-	-
Measurement sphere	~15 cm radius	~2 cm diameter	~6 L	~10 cm diameter	~3-4 L
Output reading	Raw - counts calibrated - volumetric water content (%)	% volumetric SWC	On/off switch closure	Resistance	Resistance
Installation method	Access tube	Hammered from surface	Buried in hole same diameter as instrument	Metal rod driven into soil	Buried in hole same size as instrument
Logging capability	No - manual readings may be recorded on-board for later download	Intrinsic	With external logger	Intrinsic	With external logger
Power source	12 V DC - rechargeable or alkaline batteries	12 V DC	12 V DC to test switch	12 V DC	24 V AC
Country of origin	US	Australia	Australia	Israel	Australia
Remote access	No	Via logger	Via telemetry	Via telemetry	Via telemetry
Link to other equipment	No	Via logger	Field unit solenoid operator	No	Solenoids
Interface to PC	Yes - to download	Mandatory	No	Via logger	Via controller
Affected by salinity	No	No	No	Yes	No
Expansion potential	No	Yes	Via field unit	Via logger	Yes
Technical support	High at beginning	High at beginning	High at start	High	Low
Irrigation system suited to	All	Pressure/perennial	Pressure/annual crop	Pressure	Pressure

Table 5.5

Continued

	Neutron moisture meter	AquaSensor	FullStop	Wetting depth probe	Cut-off sensor
Best soil type	All	All	All	All	All
Application	Irrigator/consultant/ researcher	Irrigator	Irrigator	Irrigator	Irrigator
Capital cost	$13,700	$230-$280 (per hammer in probe) $1250 (modular unit for 4 probes)	POA (Available only for research and evaluation)	Not available commercially in Australia	$95
Annual operating cost	New batteries	Nil	Nil	Nil	Nil
Distributor	Selby Biolab	IIS	CSIRO Land and Water.	Prof. B. Zur	IIS
Reference page	43	45	46	47	48

Note: costs as at August 2000

6. Product descriptions

Porous media

TENSIOMETERS MEASURED BY HANDHELD TRANSDUCER

SoilSpec®, Terra Tech®

Methodology
Meter-read tensiometers can be made or bought. These tensiometers must be read with a portable electronic vacuum gauge. A needle connected to the gauge is inserted into the rubber septum, and the reading is displayed on the meter (Figure 6.1). Transducers can be added into the tensiometer through a T-piece so you can connect it to a logger. Directions for the construction of tensiometers are included in Goodwin (1995).

The tensiometer must be airtight. To test this, fill it with water, place it in the sun and read it every half-day. A reading of 70 to 80 kPa should be reached before air enters the tensiometer and makes the reading to revert to zero.
To install a tensiometer, auger a hole to the desired depth. Then insert the tensiometer and surround the tip with finely ground, tamped soil to ensure excellent contact. Fill the rest of the hole with a bentonite–soil mixture to ensure water doesn't flow down between the tensiometer and the soil.

Tensiometers are capable of reading to 80 kPa, but they become less accurate past 50 kPa, as the suction causes the water to de-air (Greenwood and MacLeod 1998).

Calibration
As tensiometers measure soil: water suction you do not need to calibrate them to the soil type. The transducer in the handheld meter is pre-calibrated to kPa. No further calibration is required.

Data handling
Meters are available with and without internal memory. Manual readings can be either recorded using graph paper or entered into a PC spreadsheet. The computer gauge (SoilSpec) comes with custom software to allow downloading, viewing and storage of readings.

Maintenance
In a dry soil, water is drawn out of the tensiometer more quickly than in a wetter soil. If the level drops more than 2 cm from the top the readings become inaccurate. Check the water level in the viewing tube at least weekly, and refill the tensiometer if necessary. If it is located in a frost-prone area, you can add methylated spirits (50 mL/L water) to the tube to stop the water freezing. The rubber septum perishes and degrades after it has been pierced many times by the meter needle. Cover it and replace it regularly.

Potential limitations
> Must have a meter to take measurements, as opposed to a gauge-type tensiometer.
> Manual data collection.
> High maintenance requirement to maintain data quality.
> Difficult to convert readings to soil water content. Makes it harder to calculate the irrigation amount needed.

> Measurement range limited to 0 to 80 kPa. Becomes inaccurate after 50 kPa.
> Removing the bung during refilling can lead to movement of the tensiometer and problems with loss of soil contact.

Positive points

> Measures soil water tension – more meaningful from a plant-stress aspect.
> Simple and cheap. Easy to understand.
> No cabling required (except where tensiometers are logged).
> One meter can be used to take readings at many locations/depths.
> Better resolution in wetter soils than, for instance, gypsum blocks.
> Data can be used without further calculations.
> Not affected by salinity.

Figure 6.1

FIGURE 6.1 Home-made tensiometer (left). Commercial tensiometer/ transducer products Terra Tech (top right), SoilSpec (bottom right).

Electronic Tensiometer Meter

Rubber Plug
13mm x 100mm
"vacutainer"

Clear Plastic Tubing
5/8"OD x 1/2"ID

200mm Conduit

Ceramic Tip
20mm x 50mm
(size 1)

Gauge-type tensiometers

GAUGE-TYPE TENSIOMETERS

JetFill, Irrometer

JetFill®, Irrometer®

Methodology
These tensiometers are installed and operated in a similar way to meter-read tensiometers, but they are read via a permanently attached pressure gauge (Figure 6.2). The gauge can be replaced with a pressure transducer to enable logging.

Calibration
The gauges are preset to sea-level atmospheric pressure. For higher altitudes you can turn a screw to re-zero the gauge. No further calibration is required.

Data handling
The gauge is read manually, and you can transfer the reading to graph paper or a computer spreadsheet for storage. The data can be collected via a logger if a transducer is fitted.

Maintenance
Maintenance is similar to that for meter-read tensiometers. A vacuum pump is used to remove trapped air from gauge-type tensiometers. The Jetfill tensiometer has a small reservoir that permits rapid refilling.

Potential limitations
> Manual data collection.
> More expensive than meter-read tensiometers.
> High maintenance requirement to maintain data quality.
> Difficult to convert to SWC. Makes it harder to calculate the irrigation amount.
> Measurement range limited to 0 to 80 kPa.

Positive points
> External meter not required. You can view the reading any time you pass the tensiometer.
> Easier to maintain than meter-read tensiometers.
> Measures soil water tension – more meaningful from a plant-stress aspect.
> No cabling required (except where tensiometers are logged).
> Better resolution in wetter soils than, for instance, gypsum blocks.
> Data can be used without further calculations.
> Not affected by salinity.

Figure 6.2

FIGURE 6.2
Gauge-type tensiometer.
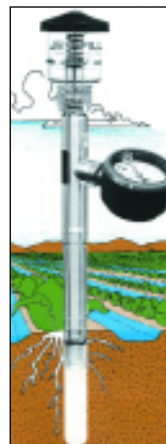
Gypsum blocks

GYPSUM BLOCKS

Methodology

Gypsum blocks consist of a pair of electrodes embedded in a block of plaster of Paris (Figure 6.3). Gypsum blocks are measured by a portable meter or remotely by a data logger. There are several different brands of gypsum blocks, each using different dimensions. These will all have different calibration characteristics and **must use** the reader designed for them. If you have a knowledge of electronics you can make your own portable meter.

To prevent polarisation of the block, use an alternating current circuit to measure the resistance between the two electrodes. One method is to apply an oscillating voltage and measure, in series with a multimeter, the alternating current through the gypsum block. Calibration curves that convert the current to soil water tension are available for the various commercial gypsum blocks. There are also several commercial meters available.

Before you install the gypsum blocks, soak them in water to remove any air pockets. Bury them at the required depth, as for tensiometers. Place finely ground soil around each block to ensure good contact, then backfill the hole with a soil–bentonite mix to stop preferential flow. Mark the wires well and tie them to a stake or vine trellis.

Gypsum blocks buffer against the effects of salinity. Determinations of soil water tension are not affected by salinity up to 6 dS/m (soil water solution), a figure higher than the salt-stress level for most crops.

Calibration

As the gypsum block measures soil water tension, you do not need to calibrate it to your soil type. The relationship between block resistance and soil water tension is very sensitive to block size, gypsum composition and electrode-separation distance. Therefore, it is better to use commercially available blocks to ensure uniformity.

Data handling

Data is recorded by a handheld meter and manually recorded or stored for download to a PC. Soil water-tension data require no further calculations and can be compared with target figures for the specific crop and growth stage.

Maintenance

Gypsum blocks are maintenance free, although as they dissolve their calibration properties change. Depending on soil type, the amount of rainfall and irrigation and the type of gypsum block, they should last from 1 to 8 years.

Figure 6.3

FIGURE 6.3 Gypsum blocks and readers/loggers.

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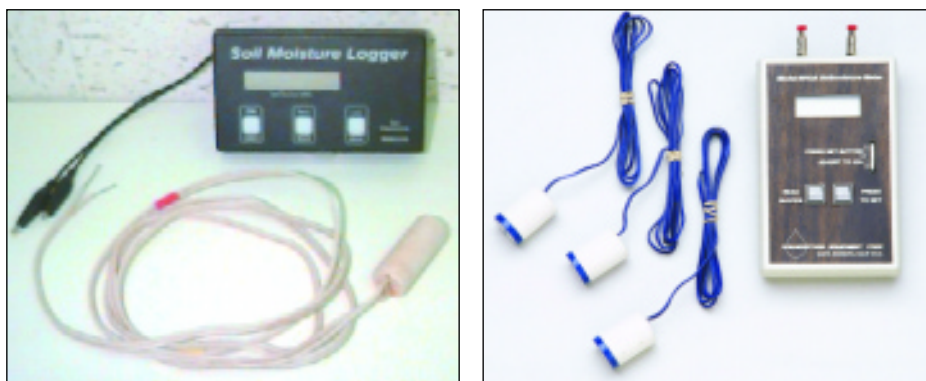
Potential limitations
> Insensitive to tension changes in wet soil (< 30 kPa).
> Must be read manually. A logging system is available.
> Measure soil water tension, which is good indication of **when** to irrigate, not **how much**.
> Blocks dissolve over time.
> Do not work well in sandy soils, where the moisture drains more quickly than the time needed for the sensor to equilibrate.

Positive points
> Simple and cheap.
> Capable of reading to low (dry) tensions (about 1000 kPa). Therefore good for drier soils and regulated-deficit irrigation.
> Measure soil water tension – more meaningful from a plant-stress aspect.
> Not affected by salinity up to 6dS/m (soil water solution).

Moisture-activated irrigation system

MOISTURE-ACTIVATED IRRIGATION SYSTEM

Methodology
This prototype product consists of an electrical resistance sensor (twin probe) linked through decision electronics to a solenoid, resulting in an 'automatic' irrigation system (Figure 6.4). The probe is measured similarly to a gypsum block but lacks the gypsum covering. Hence we have included it with 'porous media'.

The probe is installed by being pushed into the soil.

Probe resistance is calibrated to a 'wet', 'OK', or 'dry' water content. As the selected set point is passed, the controller switches the solenoid *on* or *off* to maintain an even soil water content.

Calibration
Calibration is done quantitatively. The soil around the inserted probe is wet to the desired depth and checked with a shovel. The set point control is turned until the green 'OK' light turns on. As the profile dries the 'dry' light turns on and the solenoid is activated until the resistance decreases enough to light the 'OK' light again. Manual irrigation is also catered for.

Data handling
The system is self-contained and needs no external data-recording.

Figure 6.4

FIGURE 6.4 Moisture-activated irrigation system.
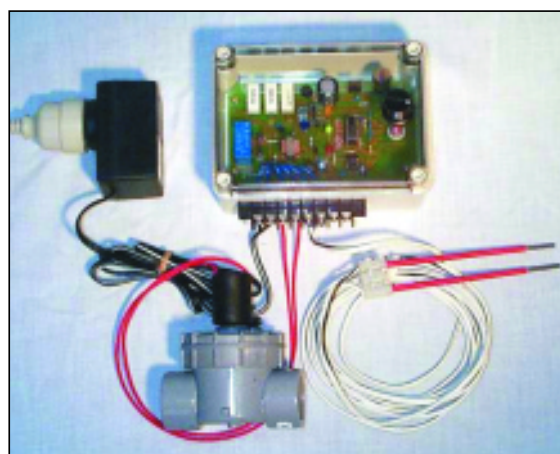
Maintenance

The instrument is relatively maintenance free, although the electronics must be kept weatherproof.

Potential limitations

> Because it is a resistance-based sensor it is subject to changes in soil electrical conductivity (EC). Fertiliser and soil EC can have a large effect on readings, at both different times and sites.
> Subjective choice of set point.
> Limited to a single-probe decision for each solenoid.

Positive points

> Cheap and simple.

Granular matrix sensor

GRANULAR MATRIX SENSOR

GBLite, Watermark

GBLite®, Watermark®

Methodology

Granular matrix sensors use the same principle as the gypsum block. Electrodes are embedded in a patented granular quartz material. This is protected by a synthetic membrane and then a stainless steel mesh (Figure 6.5). The material selected enables the sensor to measure wetter soil than a gypsum block (up to 10 kPa). The sensor includes internally installed gypsum, which provides buffering against salinity effects. This type of sensor is installed via an augered hole. Surround the sensor with fine soil, and backfill the hole with a soil–bentonite mix to stop preferential flow.

Calibration

As with gypsum blocks, granular matrix sensors are precalibrated to soil water tension (kPa).

Data handling

Data are recorded with a handheld meter and manually recorded or stored for PC download. Soil water-tension data require no further calculations and can be compared with target figures for the specific crop and growth stage.

Maintenance

Granular matrix sensors are maintenance free.

Figure 6.5

FIGURE 6.5 Granular matrix sensor. Dimensions: about 70 mm long and 20 mm diameter.

Potential limitations
> Manually read. A logging system is available.
> Measures soil water tension, which is a good indication of **when** to irrigate, not **how much**.
> Does not work well in sandy soils, where the moisture drains more quickly than the sensor can equilibrate.
> If the soil becomes too dry you must remove and rewet the sensor.

Positive points
> Simple and cheap.
> Can read to a wide range of soil water tensions (10 to 200 kPa) therefore good for a range of soils and irrigation management strategies.
> Measures soil water tension – more meaningful from a plant-stress aspect.
> Buffers against salinity effects.

Soil matric potential thermal heat sensor Campbell Scientific 229

SOIL MATRIC POTENTIAL THERMAL HEAT SENSOR
Campbell Scientific 229

Methodology

The 229 is an example of a volumetric SWC measuring device embedded in a cylinder of porous ceramic material, resulting in a composite instrument that measures soil water tension (Figure 6.6).

The device uses the heat-pulse concept, which is explained further in the section on 'Heat dissipation', to determine the water content of the ceramic material, which in turn is in equilibrium with the water tension of the surrounding soil. A heating element is placed inside a hypodermic needle, and the ceramic material surrounds the needle. When a constant power is applied to the heater, the temperature increase in the vicinity of the needle is related to the thermal conductivity of the material, which in turn is dependent on the amount of water present. Practically, the device temperature is measured before and after the heater is powered for 24 seconds. The change in temperature is the only measurement required.

The sensor can read from saturation to air-dry soil, but this capability is limited by the extent of the calibration (typically –1500 kPa).

These are installed in an augered hole. Surround the sensor with fine soil, and backfill the hole with a soil–bentonite mix to stop preferential flow.

Figure 6.6

FIGURE 6.6 Campbell Scientific's 229 sensor.
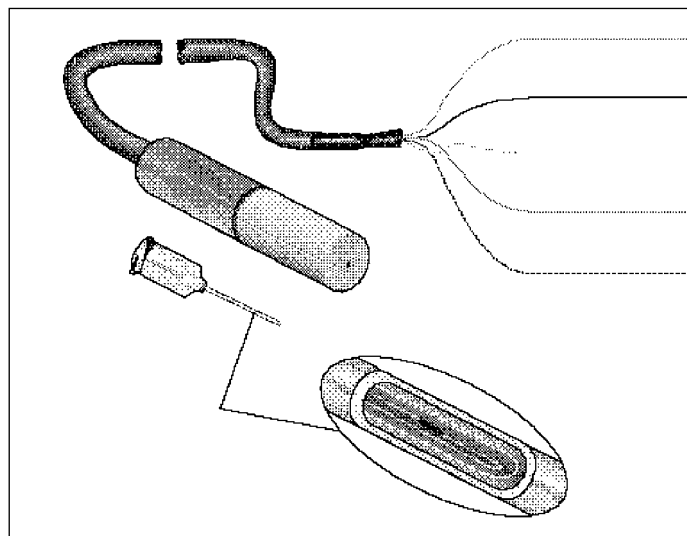
Calibration

The 229 is provided with a calibration that relates the measured change in temperature to the soil water tension (kPa). This calibration is enough for tasks where measurement changes are more important than absolute values, but individual calibration is recommended if you need greater accuracy.

Data handling

The operation of the 229 must be controlled by a sophisticated data logger capable of applying a timed voltage and measuring thermocouple temperatures. Such loggers can also be programmed with a calibration equation to give the soil water tension as a direct output. These data can then be downloaded to a PC spreadsheet.

Maintenance

No maintenance is required.

Possible limitations

> Requires a sophisticated data logger and a knowledge of logger programming.
> Measures soil water tension, which is good indication of **when** to irrigate, not **how much**.
> Does not work well in sandy soils, where the moisture drains more quickly than the sensor can equilibrate.
> Cabling is needed from the logger to each sensor.

Positive points

> Measures a wide range of tensions (limited only by the calibration range).
> Data logger operation enables automatic data collection.
> Not affected by salinity.

Equitensiometer

EQUITENSIOMETER

Methodology

The equitensiometer (Figure 6.7) consists of a ThetaProbe® (see later in this section) embedded in a specially formulated porous material. The ThetaProbe uses capacitance technology to measure the water content of the porous material, which equilibrates with the matric potential of the surrounding soil. The measured volumetric SWC is then converted to matric potential via a predetermined water-retention relationship.

Bury the sensor at the required depth. Make sure you have good soil contact: you may need to surround the instrument with a small amount of fine soil. Backfill the hole with bentonite to stop preferential flow.

Figure 6.7

FIGURE 6.7 Equitensiometer (length = 200 mm, diameter = 40 mm).

Calibration

Equitensiometers are delivered pre-calibrated. You can check the calibration, but you must return the unit to the manufacturer if it needs recalibrating. The calibration is claimed to be stable for two years. The measurement range of the instrument is 0 to 1000 kPa. Greater accuracy (± 5%) is achieved in conditions > 100 kPa. Above this pressure an accuracy of ± 10 kPa is stated.

Data handling

A handheld display (ThetaMeter®) is provided. This applies the operating voltage (5–15 V DC) and outputs raw voltage. Alternatively, a voltmeter and DC power supply or standard logger can be used and calibration applied in a spreadsheet.

Maintenance

No maintenance required. Check the calibration yearly and return the sensor to the manufacturer every two years for adjustment.

Potential limitations

> Unsuitable for use in saline soils.
> High cost.
> Needs recalibration by manufacturer every two years.
> Cabling required.

Positive points

> No maintenance.
> Large measurement range.
> Very accurate.
> More suited to drier soil.

Frequency domain reflectometry (capacitance)

EnviroSCAN®

Methodology

The EnviroSCAN system (Figure 6.8) consists of an array of capacitance sensors installed at different depths within a PVC access tube. The sensors are connected by cable to a central data logger, which powers the probes with a solar panel. A range of telemetry options can be used to offset the cable length. All sensors in the same access tube share one electronic measuring circuit, located at the top of each tube. You can set reading intervals as close as 1 minute. The standard probe lengths are 0.5, 1.0 and 1.5 m, and the maximum number of tubes per data logger is eight. Each data logger can reference up to thirty two sensors in a 500 m radius.

Installation technique is critical to the performance of devices that use the capacitance technique. The manufacturers of EnviroSCAN have developed equipment and techniques that are claimed to eliminate this problem. Once installation has been completed the equipment does not have to be disturbed again.
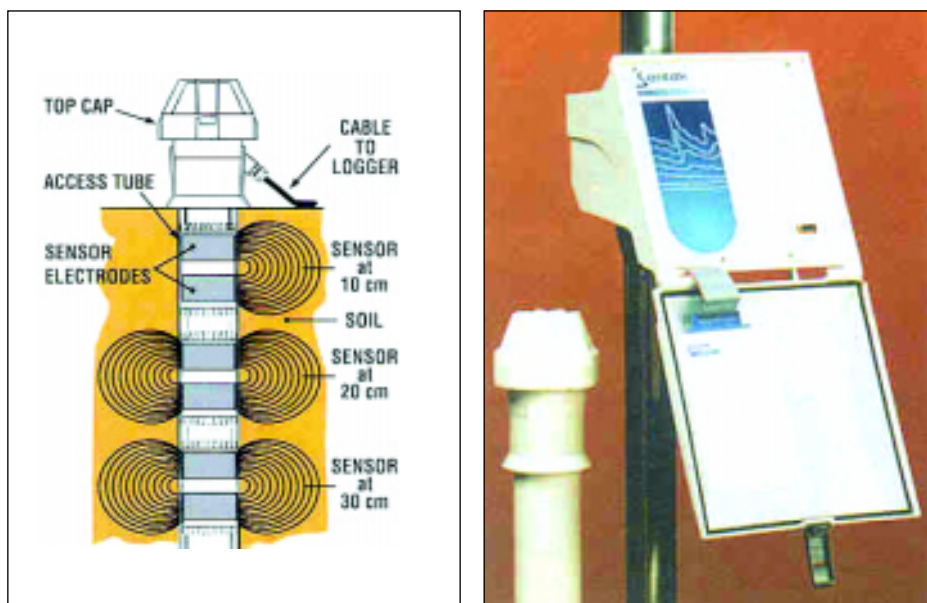
Calibration

A default calibration equation is provided with the unit. This equation is enough for most irrigation scheduling applications where only changes in stored soil water need to be measured. However, if you need absolute volumetric data, Sentek recommends that you do a specific calibration. A comprehensive procedure is provided with the unit: this basically involves sampling the soil around the tubes to determine the volumetric water content in wet, moist and dry soil.

Frequency domain reflectometry (capacitance)

EnviroSCAN

National Program for Irrigation Research and Development

FIGURE 6.8 Sentek EnviroSCAN probe, showing measurement fields (left) and logger (right).

Data handling

All data are collected at the central data logger. To view the data you must download them to a PC using proprietary software. You either take a laptop to the logger, take the removable logger to the PC, or use telemetry to transfer the data straight to the PC. The software provides several presentation options, including time-series total-profile water content and separate sensor readouts. Irrigation target setpoints may be fed in for field capacity and lower-limit water contents.

Maintenance

The equipment contains sensitive circuitry, so the most important maintenance task is to stop moisture getting into the access tubes. The sealing caps have gaskets. Silica gel bags inside the tubes must be changed regularly.

You should get the local distributor to arrange an annual maintenance check. This might include battery charging, gasket changing and backing-up of data.

Potential limitations

> Training and support are required. Skill is needed to interpret the results.
> Computer and software are required.
> Not portable. Sensors are fixed into access tubes.
> If used with annual crops, you may need to remove the cabling and tubes when the crop is finished.
> Measurement is very sensitive to the technique of access-tube installation.

Positive points.

> Robust, repeatable measurements.
> Precise depth resolution because of disc-like zone of influence.
> Automatic operation reduces labour.
> Continuous recording.
> Infiltration rate, drainage, root activity and crop water-use are easily interpreted.
> Can monitor multiple depths at the same time.
> Well suited to permanent plantings.

Diviner 2000

DIVINER 2000®

Methodology

The Diviner (Figure 6.9) uses the same soil-water-content sensing technology as the EnviroSCAN. However, Diviner is a portable system designed to be moved from site to site in much the same way as a neutron-probe moisture meter is used. The probe consists of one capacitance sensor at the end of a rod. As the rod is passed down the access tube the handheld display unit automatically records the SWC at each 10 cm depth increment. Probes are available in 1.0 m and 1.6 m lengths. It takes about two seconds to measure a 1.6 m tube.

A user manual describes all operating features, including installation procedures.

Calibration

Diviner uses a similar universal calibration to the EnviroSCAN. Customised calibration can also be input for each depth increment at each site after you have performed the same soil-sampling operation as for the EnviroSCAN. Claimed accuracy is ± 0.5%.

Data handling

A time-series record of up to 99 sites can be stored in the handheld logger. The data can be presented either graphically or numerically. Irrigation setpoints can be input to indicate the range of soil moisture allowable to avoid crop stress.

Although not required, a PC can be used to download, store and view data in standard spreadsheets.

Maintenance

None necessary. The handheld logger is powered by a rechargeable battery.

Potential limitations

> Portable manual recorder. Logging not possible.
> Some skill required to interpret results.
> Measurement is very sensitive to the technique of access-tube installation.
> The effect of salinity is unclear.

Positive attributes

> Non-radioactive, unlike the neutron probe.
> Economical way of covering many sites.
> Rapid, easy measurement.
> Avoids expensive, sensitive instruments being left in the field.

Figure 6.9

FIGURE 6.9 Sentek Diviner 2000 sensor and display unit.

C-Probe

C-PROBE®

Methodology

The C-Probe (Figure 6.10) is based on a very similar system to EnviroSCAN. It has an array of capacitance sensors installed at different depths within a PVC access tube. The C-Probe has been designed to use the Adcon® UHF radio telemetry system. The Adcon system is not sensor specific and can carry data from a variety of instruments. Software has been designed to collect weather, soil moisture and other data to provide an integrated system for both irrigation scheduling and disease prediction.

The C-Probe is available in 0.5, 1.0, 1.5 m and longer lengths. There is a maximum number of six sensors per tube/telemetry unit.

Installation issues and procedures are similar to those for the EnviroSCAN. The only cabling needed is from the sensor to the radio unit. Both the measurement and telemetry systems are powered by a small solar cell.

Calibration

C-Probe can use a universal calibration equation similar to that used by the EnviroSCAN. Alternatively, users can select calibrations for sand, loam, clay and other soil types or provide their own calibration. While a universal calibration equation is enough for many irrigation scheduling applications, the flexibility of being able to fine tune the calibration for each sensor depth can be valuable in situations such as duplex soils. If you need absolute volumetric data, do a specific calibration. An information kit and software module are provided for users who need a higher degree of calibration accuracy.

Data handling

The data-collection frequency is set by the user. Each telemetry unit automatically transmits data to a central receiver capable of handling 95 field units. The data are automatically available to the user, either by having a desktop computer connected to the receiver or via automatic download through a modem connection from other desktops or laptops. The C-Probe and Adcon software provide several presentation options, including time-series graphs and statistics showing total profile water content and separate sensor readouts. Irrigation target setpoints can be input for field capacity and lower-limit water contents, as can a comprehensive set of agronomic markers and crop-stage markers.

Figure 6.10

FIGURE 6.10 C-Probe with Adcon telemetry unit.

Maintenance

The equipment contains sensitive circuitry, so the most important part of maintenance is to stop moisture getting into the access tubes. The sealing caps have O rings, and silica gel bags inside the tubes need to be checked at least twice a year and replaced if necessary.

Get your local distributor to do a maintenance check every two years. This will include checking the O ring, swapping the silica gel bag, checking the battery and solar panel performance and checking all connections.

Potential limitations

> Training and support are required. Basic skill is needed to interpret results.
> Computer and software are required.
> If used with annual crops, you may need to remove aboveground equipment when the crop is finished.
> Measurement is very sensitive to the technique of access-tube installation.

Positive points

> Robust, repeatable measurements.
> The only cabling required is from the sensor to the telemetry unit.
> Precise depth resolution due to disc-like zone of influence.
> Automatic operation reduces labour.
> Continuous recording.
> Infiltration rate, root activity and crop water use are easily interpreted.
> Can monitor multiple depths at the same time.
> Well suited to permanent plantings.

Gopher

GOPHER®

(by Robert Hoogers, NSW Agriculture, Yanco)

Methodology

Gopher is a portable system designed to be moved from site to site in much the same way as a neutron moisture meter is used (Figure 6.11). The probe consists of one capacitance sensor at the end of a rod. As the rod is passed down the access tube, a handheld display unit records the SWC at each 10 cm depth increment.

The LCD display performs all functions of displaying and storing information, as well as calibration. The display can be linked to a PC for data storage and viewing, although this is not essential.

Calibration

Calibration is performed by taking readings when the soil is at 'Field Capacity'. The display module then calculates coefficients for each depth increment and uses these in all future readings. As with most equipment, if you need greater accuracy you will need to run a volumetric soil sampling program at two SWC levels. The coefficients calculated from this procedure can then be entered into the display.

Data handling

The display can store data for up to 48 profiles (times) from 54 sites, with sixteen depths for each site. Data can be displayed as either a volumetric SWC value or a histograph. The histographs are used to estimate the time interval before the next irrigation cycle, and also to display the usage pattern from different depths in the soil by the plants being irrigated. You can also view summed graphs that indicate total available water in the indicated profile depth.

Figure 6.11

FIGURE 6.11 The Gopher manually operated soil-moisture monitor.

Maintenance

The Gopher soil moisture profiler and soil moisture sensor are not waterproof: never handle them with wet hands or leave them exposed to the weather or irrigation sprinklers. Maintenance is centred on ensuring the access tubes are moisture free.

The equipment is fragile: handle it with care. Never use the sensor staff cable to pull the staff. Always unplug the nine-way connector by holding the body of the plug.

Never leave the Gopher or the sensor unprotected in full sunlight. This will cause an excessive temperature rise and may damage the LCD display in the Gopher. Excessive temperature increases in the sensor can produce unstable readings because of expansion of the PVC housing.

Potential limitations
> Portable manual recorder. Logging is not possible.
> Some skill required to interpret results.
> Measurement is very sensitive to method of access tube installation.
> The effect of salinity is unclear.
> The equipment is not waterproof.
> Cable connections need special care to stop them breaking.

Positive points
> Not radioactive, unlike the neutron probe.
> Inexpensive.
> Economical method for covering many sites.
> Rapid, easy measurement.
> Avoids expensive, sensitive instruments being left in the field.

**National Program for
Irrigation Research and Development**

Buddy

BUDDY®
(by Robert Hoogers, NSW Agriculture, Yanco)

Methodology
The Buddy consists of a series of Gopher capacitance sensors permanently placed in an access tube for automatic time-series logging of profile SWC (Figure 6.12). The sensor-connecting rods are manufactured to provide sensor-spacing distances of 10, 20, 30 and 40 cm. This allows the sensor string spacing to be set up with multiples of 10 cm intervals. The rods include a connector that provides the electrical connection from the Buddy data recorder through to each sensor.

The standard configuration includes four sensors and is expandable to eight.

Calibration
Two methods for calibration are available. The first uses soil sampling to gain a volumetric SWC. The second is to use a Gopher to calibrate the profile at 'Field Capacity'. The resulting coefficients are then fed into the Buddy software.

Data handling
The Buddy logger must be downloaded to a PC, either via a laptop or by taking the logger to the PC. Two graph types are available: summed profile and separate multi-line.

Maintenance
Always keep the plug and thread on the connecting rod very clean. Foreign material on the thread or connector plug such as soil will cause permanent damage and will not be covered by the equipment warranty.

Check the tube regularly to make sure there is no moisture in it.

Potential limitations
> Training and support are required. Skill is needed to interpret the results.
> Computer and software are needed.
> Not portable. Sensors are fixed into access tubes.
> If used with annual crops you may need to remove the sensors when the crop is finished.
> Measurement is very sensitive to access-tube installation technique.
> The effect of salinity is unclear.

Figure 6.12

FIGURE 6.12 Buddy in situ soil moisture monitor, showing logger and sensors.

Positive points
> Robust, repeatable measurements.
> Precise depth resolution due to disc-like zone of influence.
> Automatic operation reduces labour.
> Continuous recording.
> Can monitor multiple depths at the same time.
> Well suited to permanent plantings.

Aquaterr

AQUATERR®

Methodology
The Aquaterr consists of a single capacitance probe on the end of a rod about 1 m long. The rod is pushed into the soil to the desired depth, and the digital readout on top of the instrument gives the volumetric SWC at that depth.

Calibration
The Aquaterr does not give absolute volumetric SWC. The SWC value is a 0–100 reading, which is then related to a scale describing five moisture conditions from saturated to permanent wilting for three soil types (clay, loam and sand). The analog version of the scale is shown in Figure 6.13. Aquaterr probes that measure salinity and temperature are also available.

Data handling
Readings must be hand-recorded, along with an accurate position description. You can then enter the readings into a spreadsheet package that enables you to record changes in water content with time.

Maintenance
Charge the 9 V battery yearly.

Potential limitations
> The small measurement sphere is sensitive to small-scale variations in soil conditions. This, coupled with the different conditions encountered each time the probe is inserted into the soil, may lead to problems with repeatability.
> Penetrating dry soils is difficult.
> Hand-recording of data is time consuming, and a constant measurement position is difficult to maintain for regular reading.
> Interpretation of results may be confusing as this requires a good knowledge of soil textual changes within the measurement areas.
> The effect of salinity is unclear.

Positive points
> Readings can be taken quickly at many places in the soil profile. You can therefore track the extent of a wetting pattern at virtually any position.

Figure 6.13

FIGURE 6.13 Aquaterr instrument and analog SWC scale.
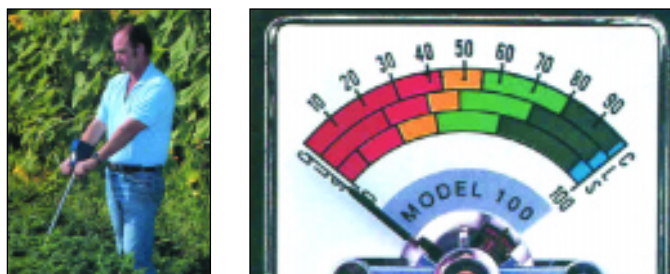
ThetaProbe

THETAPROBE®

Methodology

The ThetaProbe (Figure 6.14) avoids the limitations of an access tube by using steel spikes driven into the soil as the capacitance plates. Whereas the permanently installed multi-sensor products have one circuit that analyses each sensor serially, each ThetaProbe has its own measurement electronics within the probe head. The instrument can be either inserted into the soil surface to make one-off readings, or buried for continuous *in situ* readings. If you bury it, you should install it with an extension tube (Figure 6.14). These tubes can be left in the ground and the ThetaProbe inserted or removed when required.

Calibration

The probe outputs a measurement in volts. A calibration is then applied to the raw voltage to give volumetric water content. The literature states there is a virtually linear relationship between the voltage (0 to 1 V) and the SWC (0 to 0.5 m^3/m^3). Two 'generalised' calibrations for 'mineral' and 'organic' soils are provided; these guarantee an accuracy of 5% (0.05 m^3/m^3). Use a two-point calibration if you want to achieve an accuracy of 1% (0.01 m^3/m^3).

Data handling

A handheld display (ThetaMeter) is provided. This applies the operating voltage (5 to 15 V DC) and outputs either raw voltage readings or volumetric water content using the two 'generalised' calibrations. Alternatively, you can use a voltmeter and DC power supply or standard logger and apply the calibration in a spreadsheet.

Maintenance

The manufacturer states that no maintenance is required.

Figure 6.14

FIGURE 6.14 ThetaProbe. (Top length = 200 mm, diameter = 40 mm.) Bottom shows installation suggestion and ThetaMeter.
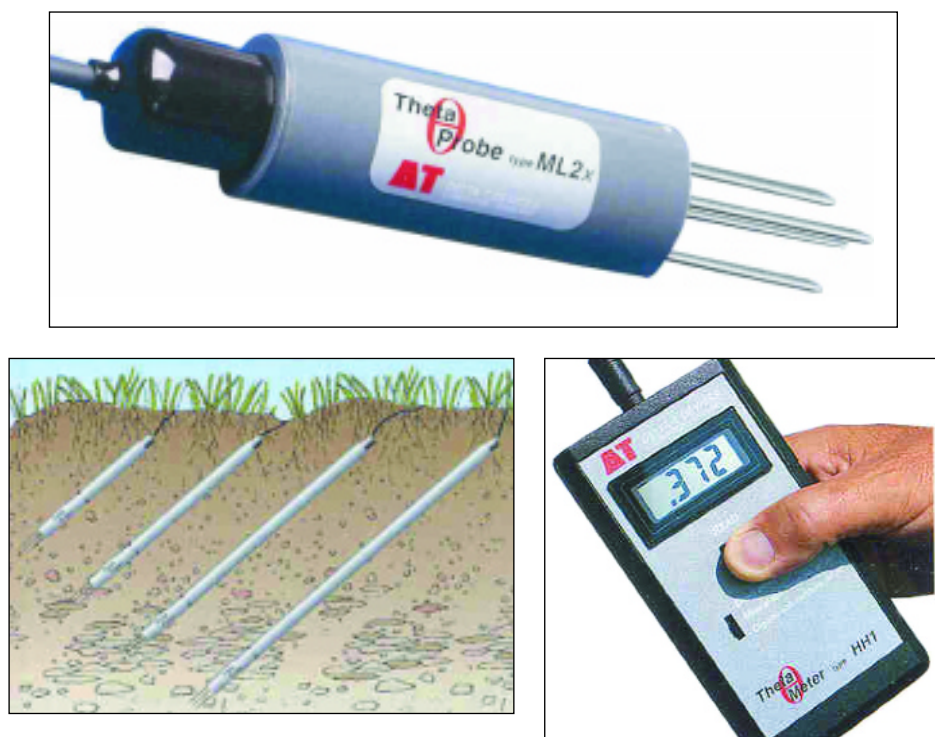
Potential limitations
>   Manually read.
>   Replication of circuitry adds to the expense when using instrument arrays.
>   Hard to push probe into dry soil.
>   Minimal salinity effect.

Positive points
>   Inserting probes into soil greatly enhances contact.
>   Signal processing is completed at the instrument, leaving a simple voltage output.
>   The instrument arrays can be spatially distributed, for example, throughout a root zone.

Netafim soil moisture data collector

NETAFIM SOIL MOISTURE DATA COLLECTOR

Methodology
The Netafim soil moisture data collector consists of up to three 3-rod probes connected to a data logger (Figure 6.15). The system uses a capacitance technique where the probes are the plates and the surrounding soil is the dielectric.

A switching circuit actuates the charging and discharging of the capacitor between two constant limits. The frequency of this cycle is inversely proportional to the water content of the soil. This output is fed into a frequency-to-voltage converter that integrates the frequency into a proportional voltage, which may be read with a voltmeter. The probes are buried at the required depth.

Figure 6.15

FIGURE 6.15 Netafim soil moisture data collector.

Calibration

The sensor output data is presented in 'soil moisture units' with a practical range of 30 to 80. As with other sensors that do not rely on absolute soil-water-content measurement, 'calibration' refers to identifying the irrigation full and refill points. This is done by analysing several dry-down cycles. These show the point where post-irrigation drainage ends (full point) and where crop water extraction from the profile slows (refill point).

Data handling

The logger holds up to 960 readings or about one week of data, with three probes recording every 30 minutes. When the logger is full the data collection halts. You need a PC or laptop for downloading and viewing data.

Maintenance

The only maintenance required is cleaning of the logger and enclosure, and battery replacement.

Possible limitations

> The probe is insensitive at high water contents.
> It is hard to relate the output units to the irrigation amount applied or to evapotranspiration calculations.

The salinity effects are not stated by the manufacturer (see first positive point below).

Positive points

> Unaffected by salinity in normal range of irrigation water/soil.
> Simple, self-contained system.
> Relatively cheap.

Time domain reflectometry (TDR)

TEKTRONIX 1502 TDR CABLE TESTER

Methodology

The Tektronix TDR cable tester (Figure 6.16) consists of a voltage pulse generator, a timing circuit and a cathode ray oscilloscope that displays the voltage waveform. You need a PC or laptop with the relevant software to interface with the TDR to analyse the waveform start and end points, store data and switch from probe to probe if multiplexing.

The unit is large (127 x 315 x 436 mm) and heavy (6.5 kg). Because of its size and the need to have a PC or laptop attached, the Tektronix is used more for permanent buried wave-guide installation, not for portable readings.

Wave guides usually consist of two- or three-pronged stainless steel probes. The optimum probe length is 30 cm, but in soils with high attenuation, shorter probes (minimum 10 cm) may be required. When you are burying the probes, insert them into the side of a small trench to make sure they go into undisturbed soil.

Calibration

The PC software allows you to feed in specific calibration coefficients. The universal calibration gives very good accuracy for a wide range of mineral soils. If you are using other materials or organic soils, you may need to do a custom calibration involving soil sampling to determine volumetric SWC.

Data handling

A PC or laptop is used to operate the Tektronix and store data automatically. Stored data can be downloaded, manipulated and presented in a spreadsheet.

Possible limitations
> Expense.
> High training requirement.
> Size and weight – not suitable for portable use.
> Requires a PC or laptop.
> Small size of measurement sphere makes the unit sensitive to the region immediately next to the probe wires.
> Attenuation of the signal caused by salinity or highly conductive heavy clay soils may lead to inaccurate readings.
> Limited cable length between wave guide and voltage generator.

Positive points
> Universal calibration.
> Excellent accuracy and precision.

Figure 6.16

FIGURE 6.16 Tektronix 1502 TDR cable tester with laptop and enclosure.
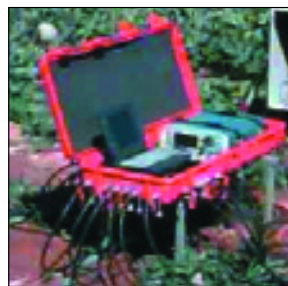
TRASE TDR

TRASE® TDR

Methodology
The TRASE (Figure 6.17) is purpose built as a soil (or other media) moisture meter. Therefore, as well as having a pulse generator, timing circuit and display, it has onboard software that can analyse the waveform and detect the signal-trace start and end points. The TRASE is also equipped with memory that can store both locations and SWC values or whole waveforms for later reference.

Accessories that enable autologging and multiplexing are available.
The basic unit is large (200 x 300 x 400 mm) and heavy (7 kg).

Wave guides usually consist of two- or three-pronged stainless steel probes. The optimum probe length is 30 cm, but in soils with high attenuation shorter lengths (minimum 10 cm) may be required. When you bury the probes, insert them into the side of a small trench to ensure they are going into undisturbed soil.

Calibration
The universal calibration in *Appendix 2* is included with the TRASE. This gives very good accuracy for a wide range of mineral soils. If you are using other materials or organic soils, you may need to do a custom calibration that involves oven-drying soil samples.

Data handling
The TRASE outputs the dielectric constant and volumetric SWC. These can be manually recorded or stored in memory and downloaded to a PC. Accessories are available for direct downloading from a remote unit to a PC via telemetry.

Possible limitations
> Moisture can get into the connections of buried wave guides and lead to unstable traces.
> Relatively heavy and cumbersome when used as a portable unit.
> High bulk density, clay, or saline soils cause a weak signal return, which makes it hard to recognise end points.
> The distance from the wave guide to the analyser is limited to 35 m.
> Expense.
> If this is used as a portable system, the wave guides are difficult to insert into dry or crusted soil.

Positive points
> Extremely accurate.
> Easily expanded by multiplexing.
> On-board data storage.
> Immediate output of absolute SWC.

Figure 6.17

FIGURE 6.17 TRASE TDR.

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Campbell Scientific TDR100

CAMPBELL SCIENTIFIC TDR100

Methodology
The TDR100 (Figure 6.18) is the smallest true TDR processor available. As with the Tektronix, it needs a logger or PC to operate. The basic specifications show the unit to be very small (21 x 11 x 5.5 cm), and it weighs 700 g. The price is expected to be half that of the Tektronix unit.

Calibration
The universal calibration in *Appendix 2* is included with the TDR100. This is very accurate for a wide range of mineral soils. If you are using other materials or organic soils you may need to do a custom calibration involving oven-drying soil samples.

Data handling
The most common configuration of the TDR100 will be as part of a multiple wave-guide multiplexing system. Campbell data loggers and multiplexers that manage the readings and log the data are available. Software is available to enable a PC to make readings and switch the multiplexor.

Possible limitations
> Must be used with a PC or logger.
> Moisture can get into the connections of buried wave guides and lead to unstable traces.
> The small size of the measurement sphere means that the unit is sensitive to the region immediately next to the probe wires.
> Attenuation of the signal caused by salinity or highly conductive heavy clay soils may lead to inaccurate readings.
> Limited cable length between wave guide and voltage generator.

Positive points
> Very small and light.
> Excellent accuracy.
> Easily expanded by multiplexing.

Figure 6.18

FIGURE 6.18 Campbell Scientific TDR 100.

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Irrigation Research and Development
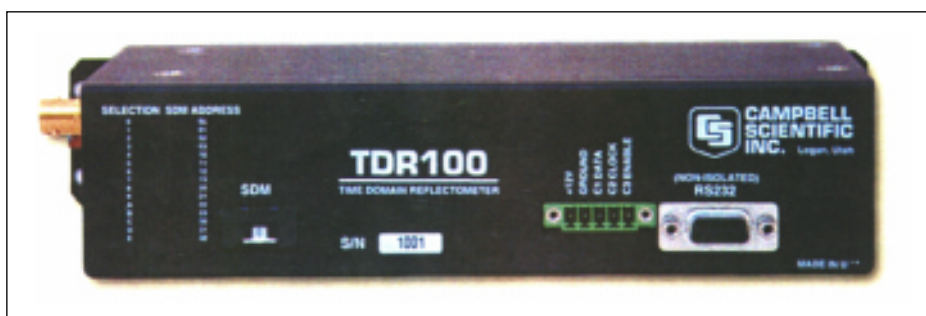
Water content reflectometer (Campbell 615)

WATER CONTENT REFLECTOMETER (CAMPBELL 615)

Methodology
The Campbell 615 (Figure 6.19) consists of a 30-cm wave guide with the measurement electronics built into the probe head. The major difference between the 615 and the 'true' TDR equipment is that the 615 doesn't directly measure the wave-guide signal reflection time. Instead, the signal return from the guides causes a circuit (a bistable multivibrator) to change states between two discrete values. The output of the sensor is a frequency that reflects the number of state changes per second (or Hz). As with all TDR sensors, a wetter soil will cause a longer signal-return time, and will cause the 615 circuit to vibrate at a lower frequency.

The wave guides can be buried for *in situ* readings or used as a portable probe.

Calibration
Calibration relates the output signal frequency to the volumetric water content. A calibration equation has been developed for a loamy fine sand. It has an accuracy of ± 2%. The product literature states that the same equation has been used with a range of mineral soils with an accuracy of ± 2.5%.

The 615 has the disadvantage of being affected by salinity in soils of salinity > 2 dS/m. Custom re-calibration is required to optimise accuracy. The probe output becomes unstable at conductivities > 20 dS/m.

Data handling
A meter or datalogger capable of frequency measurement is required. A handheld meter, the HydroSense®, is produced by Campbell Scientific Australia. It outputs volumetric water content. This meter can also store multiple calibration equations.

Possible limitations
> Needs a meter capable of reading a frequency.
> Affected by salinity > 2 dS/m.

Positive points
> Handheld mode for manual readings at multiple sites.
> Good accuracy.
> Large measurement volume.

Figure 6.19

FIGURE 6.19 Campbell 615 water content reflectometer with HydroSense handheld reader.

Aquaflex

AQUAFLEX®

Methodology

Aquaflex uses time delay transmission (TDT) to measure the soil dielectric. The sensor consists of a 3 m-long dual-core wire with a flexible plastic coating (Figure 6.20). The two wires are joined at the end to form two complete loops for signal transmission. In the same way as the Campbell Reflectometer, the sensor measures the signal oscillation frequency, which is related to the surrounding material dielectric. Information is extracted from the shape of the transmitted pulse, which gives a good indication of soil conductivity and is used to compensate the moisture-measurement reading to maintain accuracy in conductive soils.

The length of the sensor (3 m) is specifically designed to overcome the problem of a small measurement sphere common to most instruments. Aquaflex sensors sample about 6 L of soil when a measurement is taken.

The probes are installed horizontally or diagonally into a trench. Any soil disturbance can create unrepresentative conditions, and so it is recommended that you install the units during initial land preparation to ensure all parts of the field settle to an even condition (Wood 1999).

Calibration

The manufacturer provides a range of calibration equations easily selected in the PC software, and they can be used for a wide range of soil types. Again, this is sufficient for most irrigation scheduling applications where only changes in stored soil water need to be measured. However, if you need absolute volumetric data, do a specific calibration. As the instrument is both long and installed horizontally, you can do this easily with soil samples or TDR probes for SWC, or with tensiometers for calibrating to soil water tension.

Data handling

Each sensor is connected via a cable to a logger that stores both soil water content and temperature data. An Aquaflex logger is available, but other commercially available loggers can be used. A palmtop or laptop computer can then be used to download data and shuttle back to a PC; alternatively, telemetry is available for remote download. Data can be viewed in either the custom software or a spreadsheet program. An Aquaflex handheld reader can also be used. The custom software allows you to insert soil full and refill points for irrigation scheduling.

Maintenance

Wood (1999) states that the only maintenance tasks were; keeping the solar panels clean of dust and bird droppings, ensuring the batteries were charging and keeping the logging units free of pests such as ants and spiders. The device proved to be extremely reliable.

Figure 6.20

FIGURE 6.20 Aquaflex sensor with high quality data cable and connector.

Potential limitations
> Soil disturbance during installation.
> The cable to the logger is susceptible to damage.
> As with all dielectric sensors, the calibration is non-linear: more samples must be taken for a non-standard calibration.

Positive points
> Moisture measurement is averaged over a 3 m-long cylindrical volume (6 L)
> Direct measurement of soil temperature.
> Moisture measurement compensates for both soil conductivity and soil temperature.

Gro-Point

GRO-POINT®

Methodology
The Gro-Point uses the time-delay transmission concept to measure the soil dielectric. The probe is available in two configurations. The standard device (Figure 6.21) consists of three stainless steel rods, each about 25 cm long, with the outside two joined to form a loop. An extended-range sensor is also available; it measures a larger soil volume and is designed for greater accuracy in both high clay and high sand soils. The Gro-Point is buried at the required position in the root zone.

Figure 6.21

FIGURE 6.21 Gro-Point soil moisture sensor: standard and extended models and handheld reader.

Calibration
Probes are factory calibrated with a stated accuracy of ± 1%.

Data handling
Cabling leads either to where the handheld reader can be attached or to a logger. Gro-Point software enables data collection and graphing.

Maintenance
The only maintenance required is cleaning and changing batteries in the handheld sensor or the logger.

Possible limitations
> Calibration cannot be changed.
> Probe design precludes insertion into undisturbed soil.
> Salinity effects at high levels.

Positive points
> Relatively large sampling area, especially with the extended model.
> Simple to read.
> Relatively inexpensive sensors, loggers and software.
> Can be integrated into a larger irrigation system by way of a logger.

Neutron moderation

Neutron moisture meter

Neutron moderation

NEUTRON MOISTURE METER

Methodology

Because of their high cost, neutron moisture meters (NMMs) are usually bought only by larger organisations. For smaller operations most regions have consultant services that provide both measurement and advice on irrigation scheduling.

The NMM consists of a nuclear source/detector suspended from a cable, and a housing that contains the count/storage electronics and a shield for safe transportation of the source (Figure 6.22).

Aluminium access tubes with bottom stops are installed at the required site with an auger or a hydraulic ram. As with all instruments that use access tubes, you must take care to get good soil contact. Protect the top of the tube from rainfall: an aluminium can usually gives enough cover.

The NMM is placed on top of the access tube and the source/detector is lowered down the tube to the required depth. For ease of use, metal tags are attached to the cable to mark the depth increments. At each depth the operator pushes a timer button to start the NMM counting the returning neutrons. The accuracy of the readings is related to the length of the measurement time; 16 or 32 seconds is recommended. When the readings are finished for one tube, the source is retracted into the shield and either moved to the next tube or returned to its shipping case.

The soil volume measured by the NMM varies inversely with the water content, but an average figure of 15-cm radius may be assumed. This large measurement radius means that air gaps in the access tube have only a minimal effect on readings.

In Australia you need a licence to own, operate and store an NMM. You must wear

Figure 6.22

FIGURE 6.22 Neutron moisture meter (photo at left: Utah State University 1999).
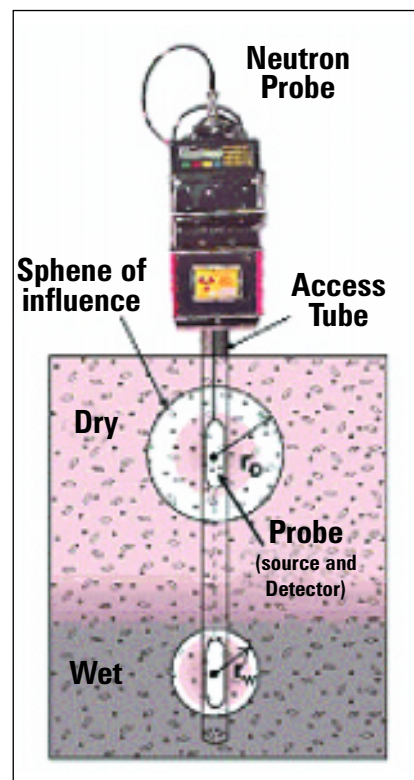
a radiation-exposure tag while operating the NMM, and you must return it to the issuing authority for periodic checking.

The perceived threat of radiation exposure is one of the biggest problems for the NMM. Despite this perception, a recent article addressing the safety issue stated that in over 40 years of use there had been no known breach of the doubly encapsulated radiation source even when 'incidents' have included instruments being crushed by earthmoving equipment or falling from high buildings (Evett 1999).

Calibration

Two forms of NMM calibration are required. First, readings are taken relative to a 'drum count', that is, the count when the source is lowered down a tube placed in the centre of a drum full of water. A 'drum count' is taken to minimise potential drift in instrument readings and should be performed each season.

Second, the NMM must be calibrated to the soil in which it will be used. Universal calibration equations are available, but again, if you need greater accuracy you should do a custom calibration. This consists of a two-point linear regression of volumetric water content (measured from soil cores) versus the NMM reading. You can take gravimetric soil cores while installing the access tubes, destructively, or near the installed access tube.

Data handling

The raw count appears on a screen and can be manually recorded or logged for later download. The calibration equation can be incorporated into a spreadsheet for easy data interpretation. Alternatively, there are commercial software packages that handle neutron-probe data and irrigation scheduling (for example, WATSKED, 'The Probe').

Maintenance

Check for instrument drift each season. The unit is powered by rechargeable AA batteries, which should be cycled regularly. The radiation source is not waterproof, so you must check the access tubes to make sure no moisture has entered after rainfall.

Possible limitations

> Manual reading.
> Public perception of radiation safety threat.
> Relatively long time taken for each reading: eight depths at 16 seconds per reading means 2.5 minutes per tube.
> Heavy, cumbersome instrument.
> Calibration. This is especially an issue if you are carrying the instrument between markedly different soils.
> Large volume measurement makes readings close to the surface difficult.

Positive points

> The most robust, accurate, proven method available for measuring soil water content.
> Measures a large volume of soil.
> Not affected by access-tube air gaps.
> Not affected by salinity.

Heat dissipation

AQUASENSOR®

Methodology

The AquaSensor combines a heater and thermometer in a stainless steel canister 70 mm long and 8 mm in diameter (Figure 6.23). The measurement is performed via modules capable of reading either four or eight probes. All systems must be linked to a PC for data storage and viewing. The AquaSensor is part of an irrigation system control and data acquisition system that can be operated either manually or automatically. The probes are hammered into the ground to the required depth.

Calibration

As with other sensors that do not rely on absolute soil-water-content measurement, 'calibration' refers to the identification of irrigation full and refill points. This is done by analysing several dry-down cycles. These show the point where post-irrigation drainage ends (full point) and where crop water extraction from the profile slows (refill point).

Data handling

The AquaSensor is part of an irrigation system control and data acquisition (SCADA) network that can be operated either manually or automatically. In manual mode the user views the sensor information and makes a decision about irrigation. In automatic mode, threshold levels (refill and full points) are set. When these are passed the software will turn the pumps or solenoids on or off.

Maintenance

The only maintenance required is ensuring that the above-ground enclosures are clean and watertight, and that the batteries are charged.

Possible limitations
> Small measurement sphere. Many measurements may be needed if the conditions are highly variable.
> Slow measurement time (about 5 minutes for each reading).
> Raw data cannot be accessed.

Positive points
> Small measurement sphere. High spatial resolution.
> Minimum soil disturbance with small-diameter hammer-in probes.
> Part of larger SCADA system.
> Not affected by salinity.

Figure 6.23

FIGURE 6.23 AquaSensor hammer-in probes with moisture-probe module.

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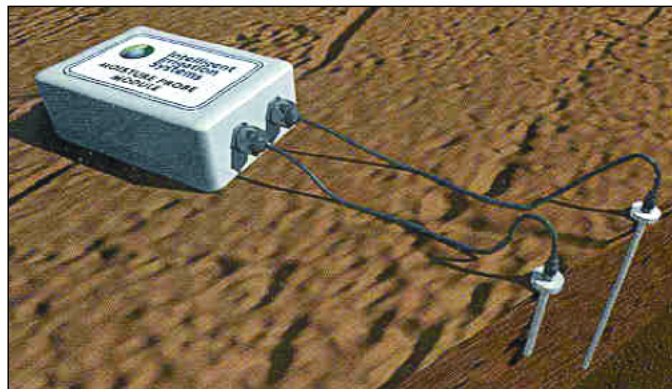
Wetting-front detection

Any soil-moisture sensor that can distinguish between 'wet' and 'dry' soil, and has outputs that indicate these two conditions reliably, can be used as a wetting-front detector. However, to meet the requirement for low unit cost, only two methods of measuring soil moisture have been used in detectors. These are measuring soil moisture by using the electrical resistance of a porous material and detecting the flow distortion around a buried object. The first method is used in the 'wetting-depth probe' and the 'cut-off sensor', while the latter is used in the FullStop®.

The products that use this technology are new and, although they offer great potential, they have not been proven in the wide variety of commercial situations required to define their ultimate strengths and limitations.

FullStop

FULLSTOP®

Methodology
The FullStop is a funnel-shaped object that has a hollow cylindrical ceramic filter and an electrical float switch at its base (Figure 6.24). After irrigation, the wetting front arrives at the lip of the funnel. The soil water content in the funnel increases because the funnel distorts the wetting front. The soil water content at the base of the funnel increases to the point of saturation, and water flows through the filter to raise the float switch. Some of the water that passes through the filter flows into a reservoir. This water can be collected after the irrigation by extraction through a tube with a syringe. As the soil surrounding the FullStop dries, the water remaining in the filter is withdrawn back into the soil by capillary action and the FullStop is reset ready for the next irrigation.

Calibration
The FullStop requires no calibration for soil type or sensitivity. It can detect wetting fronts in all soils with all known methods of irrigation.

Data handling and interpretation
The output from a FullStop is an electrical contact closure. It can be connected directly to a water solenoid so that irrigation stops when the soil is full, connected to an audible or visual alarm, or connected to the field unit as part of an array of six FullStops.

When the FullStop is used in conjunction with the field unit, the wires from six units are connected to a small transmitter mounted on a post in the crop. The moment a FullStop is activated, a light on the panel in the pumphouse (or other convenient location) illuminates. The panel also has a rotary dial going from 1 to 6 and a four-digit display. When the number of units that have detected water corresponds to the

Figure 6.24

FIGURE 6.24 The FullStop and field unit.
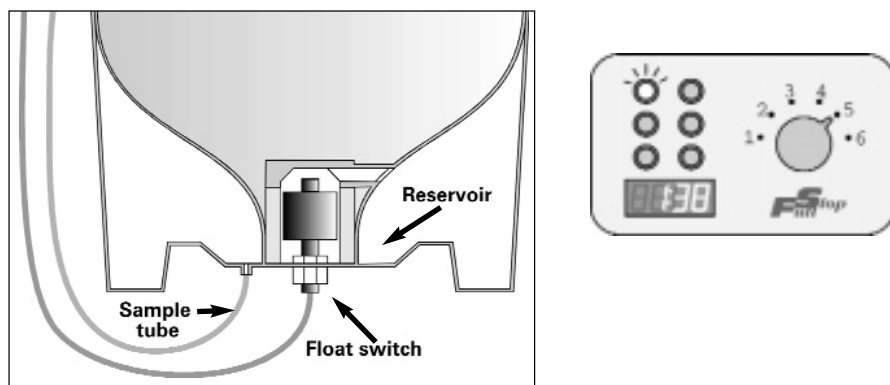
number selected on the dial, a relay is closed, indicating that irrigation should stop. This relay can be connected to a conventional irrigation controller. The four-digit display shows the time elapsed between turning on the irrigation and the relay closing. This information, along with the individual FullStop signals, is logged internally and can be used to plan irrigation shifts.

Maintenance
The FullStop requires no maintenance and uses no power. The field unit is powered by 12 V DC.

Potential limitations
The FullStop is large (20 cm diameter), and a hole of the same size needs to be dug during installation. If you are using the unit in perennial crops, where root and soil disturbance must be minimal, you must seal the upper portion of the augered hole with bentonite so that the FullStop responds to wetting fronts propagating through undisturbed soil.

Positive points
> As the FullStop collects soil water from every wetting front, it can be used as a management tool to monitor the movement of solutes such as salt and nitrate.
> Inexpensive.
> Easily interpreted.
> Not affected by salinity.

Wetting-depth probe

WETTING-DEPTH PROBE

Methodology
The wetting-depth probe is a long, narrow rod made up of eight sensors embedded at 5-cm intervals. Each sensor is a hollow cylinder of a porous material with thin, ring-shaped stainless steel electrodes tightly fitted at the upper and lower ends (Figure 6.25).

The electrodes are connected to an electronic controller. When the wetting front reaches a particular sensor, the resistance between the electrodes decreases. This signal is recorded by the controller and used to calculate the velocity of the advancing wetting front. When you know the wetting-front velocity you can calculate the irrigation cut-off time needed to stop the wetting front at the design depth.

Figure 6.25

FIGURE 6.25 The wetting-depth probe.
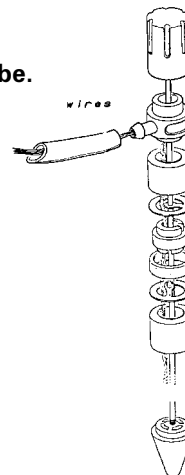
Calibration
The wetting-depth probe requires no calibration for the soil type, but it is expected to depend on the conductivity of the water in the wetting front.

Data handling and interpretation
The wetting-depth probe is used in conjunction with a theory on wetting-front move-
ment that is installed within software in the controller. The program takes input from
the user and automates the process of determining the depth at which you should turn
off the irrigation (Zur *et al.* 1994).

Maintenance
The wetting-depth probe requires minimal maintenance.

Potential limitations
The wetting-depth probe is part of a larger irrigation-control system and may not be
flexible enough to be adopted by a wide range of irrigators. It is affected by salinity,
but the extent is unknown.

Positive points
The wetting depth probe can be used to 'program' the depth of wetting-front move-
ment into an automatic control system to match the vertical growth of a root system.

Cut-off sensor

CUT-OFF SENSOR

Methodology
The cut-off sensor is a rectangular plastic card 20 x 10 cm that is covered in geotex-
tile. Two parallel copper rods are glued to the face of the card and are connected by
cables to an electronic controller. The controller is fitted in the power line to the sole-
noid valve. When the wetting front arrives at the cut-off sensor, the geotextile becomes
wet and the electrical resistance between the two rods decreases. This change is detect-
ed by the electronics, and the power to the valve is turned off. As the soil dries the
resistance increases and the sensor is reset for the next irrigation.

Calibration
The cut-off sensor requires no calibration for soil type or sensitivity, but the calibra-
tion is expected to depend on the conductivity of the water in the wetting front.

Data handling and interpretation
The cut-off sensor turns off the irrigation solenoid valve and stops irrigation. The con-
troller can also be used to turn on the next valve in sequence

Maintenance
The cut-off sensor requires no maintenance.

Potential limitations
> Depends on the electrical conductivity.
> Needs 24 V AC.
> The soil is disturbed when it is installed in perennial systems.
> Can be incorporated in a system of multiple detectors within one irrigation
bay.
> Affected by salinity, but the extent is unknown.

Positive points
> Easy interpretation.
> Inexpensive.
> Easily interpreted.

7. CASE STUDIES

WATER USE BY FURROW-IRRIGATED ONIONS ON A CLAY SOIL

(by Dennis Muldoon, Mark Hickey and Robert Hoogers – Yanco Agricultural Institute, NSW and Mohammed Aleemullah and Bill Ashcroft – Institute of Sustainable Irrigated Agriculture, Tatura, Victoria)

Reprinted from *Farmer's Newsletter* (June 1999) No. 183 – *Horticulture, Irrigation Research and Extension Committee.*

In a nutshell: Onions can draw moisture from a depth of 50 cm.

Over 800 ha of onions are grown on self-mulching clay soils in the Murrumbidgee Irrigation Area (MIA). Most of this area is formed into 1.5 or 1.8m beds and furrow irrigated. Onion growers are facing the challenges of increasing limitations on water availability, rising water tables and salinity, as well as market demands to produce a top quality product. To achieve sustainable production, soil water dynamics must be better understood.

Site details

The study was undertaken on a 12-ha commercial crop of Creamgold onions at Whitton in the MIA. The soil was Wunnamurra Clay. The 1.5m beds were 500 m long, with a slope of 0.07%. The onions were sown in five rows per bed and watered up with furrow irrigation (Figure 7.1). During winter no irrigation was needed, as the rainfall was above average. The first irrigation in the spring was on 30 October 1998.

FIGURE 7.1 Bed configuration used in the trial.

Gopher access tubes were installed in the centre of a bed, one 50 m from the top and another 50 m from the bottom of the run. The sensor was inserted into the access tubes to give readings at various depths. Readings at 10 cm intervals to a depth of 100 cm were taken frequently. The readily available water (RAW), or the amount of water stored between the field capacity (FC) and the 600 cm suction (refill point), has been estimated at 90 to 100 mm for this soil type (Aumann *et al.* 1998). For the soil at this site, the top 50 cm of the profile was estimated to have an RAW of 40 mm.

Findings

Figure 7.2 shows the changes in soil water content with depth during an irrigation cycle. The first irrigation of the crop on 30 October brought the soil back to field capacity (full point) at the top of the run, but not at the bottom. (The irrigation was cut off too soon.) The water-use graph shows how the onion crop extracted water over the following 20 days, first from the surface layers, then ultimately down to a depth of 50 cm. The surface soil dried down below the wilting point to just 8 mm/100 mm. The water use extended down to 50 cm as the crop progressively used soil water. Below 50 cm there was no water use, so the water use remained at full point or field capacity.

Figure 7.2

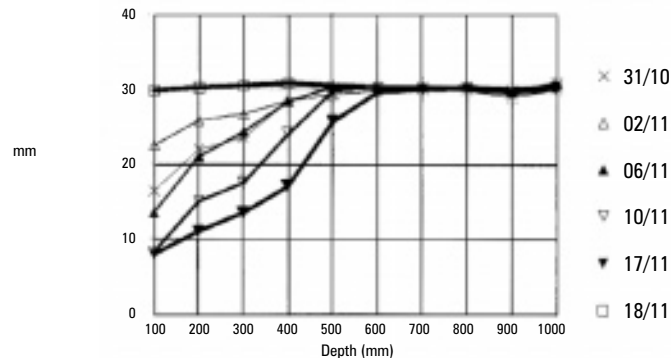**FIGURE 7.2 Water-use graph for the bottom of the run.**

Figure 7.3 shows the summed histograph or changes in soil water content in the root zone (0 to 50 cm) over time.

The three irrigations during spring and summer effectively 'filled' the soil profile, except at the bottom of the run in the October irrigation. This irrigation was terminated prematurely in an effort to reduce tail-water losses. The following irrigation was continued much longer, to the extent that the profile was saturated for two to three days. The first two irrigations were applied after the soil water content was well below the refill point. The third and final irrigation was applied much sooner to avoid stressing the crop. This irrigation, 18 days before harvest, allowed complete drying down of the onion crop.

Figure 7.3

FIGURE 7.3 Changes in soil water content at top (left) and bottom (right).
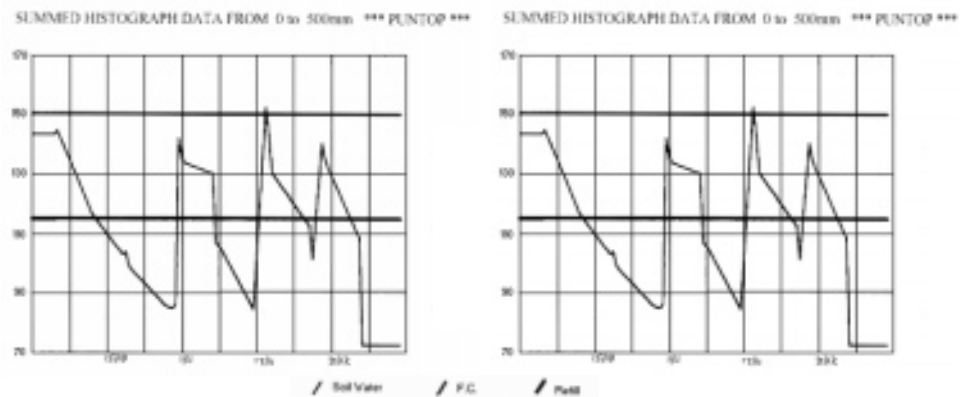
The crop yielded 65 t/ha of fresh onion bulbs. Average bulb weight was 153 g. The grower estimated that 1 ML/ha of water was applied each irrigation, giving a total of 4 ML/ha for this crop. Actual water taken into the profile each irrigation and used by the crop was about 0.6 ML/ha, or a total of 2.4 ML/ha. In addition to this, the crop received 295 mm (2.95 ML/ha) of rain during the growing season, mainly in the winter.

Conclusions

> Onions grown on medium to heavy clay soils in the MIA can extract soil moisture to a depth of 50 cm.
> Onions in the MIA can be grown with 3 to 4 ML/ha of irrigation water.

Reference

Aumann C., Ashcroft W. and Cass A. (1998) Benchmarking soils for processing tomato production. *Australian Processing Tomato Grower* 19:18–20.

Rooting depth of irrigated rockmelons on clay soils

ROOTING DEPTH OF IRRIGATED ROCKMELONS ON CLAY SOILS

(by Dennis Muldoon, Mark Hickey and Robert Hoogers – Yanco Agricultural Institute, NSW and Mohammed Aleemullah and Bill Ashcroft – Institute of Sustainable Irrigated Agriculture, Tatura, Victoria.)

Reprinted from *Farmer's Newsletter* (June 1999) No. 183 – Horticulture, Irrigation Research and Extension Committee.

In a nutshell: Understanding root growth plays an important role in irrigation scheduling.

Vegetable growers spend a lot of time looking after the above-ground part of their crops but must remember that generally the same amount of crop mass is below the ground. And it is this below-ground mass, that is the roots, which plays the vital role of seeking and supplying water and nutrients for the growing crop.

Rooting depth in particular is of utmost importance to the irrigator. Applying water until it goes beyond the rooting depth of the crop is not only wasting costly water but can contribute to rising watertables or nutrient leaching or both. Similarly, not applying enough water to wet the whole root system will mean more frequent irrigations and may lead to a shallow, restricted root system.

Over the years scientists and farmers have tried many ways to find the pattern of root growth in the soil. They have laboriously dug holes, sieved roots from soil and built underground chambers to observe and measure root growth. But modern technology designed for irrigation scheduling gives the added benefit of determining where roots are actively extracting water from the soil.

The EnviroSCAN is one such electronic system that measures the dielectric constant of the soil–water mix, and converts this to a soil water content. It can be set to log soil moisture content at frequent intervals during the life of the crop.

A network of sensors was installed around plants in the field and the logger was set to record every 30 minutes. The data were then reproduced as a graph, which shows a diurnal pattern of change in the soil water content when plants are extracting water (Figure 7.4). At night, when the leaf stomata close, plant water loss through transpiration is minimal so the graph is flat. As the sun emerges the plant 'switches on' and begins to transpire. The graph changes from a flat line at night to a steep decrease during the daytime.

Rooting pattern

The rockmelon is a dicotyledenous plant with a tap root system. It has potential to grow deep in the soil, depending on soil structure (bulk density) and water content. The actual rooting depth of this crop has seldom been recorded. Nevertheless, rooting depth is generally considered to be 50 to 60 cm (Lovatt *et al*. 1997, Sanders 1993).

Figure 7.4

FIGURE 7.4 Changes in soil water content
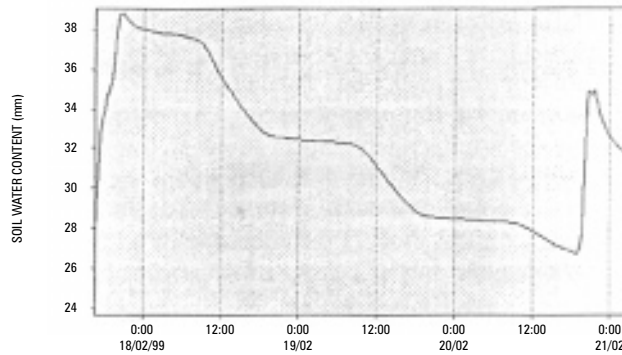
From Figure 7.4 changes in soil water content occurred over a three-day period at 40 cm depth in a rockmelon crop. Note decrease from 0900 to 1800 h each day (plant water use) and steady state during the night (no plant water use).

The experiment

EnviroSCAN installation.

At the Whitton site we installed three access tubes 10, 20 and 30 cm away from the plant row in a drip irrigated crop. The soil was a Wunnamurra Clay with a texture change from clay loam to medium clay at 35 to 40 cm. There was a single drip line buried at 10 cm in the centre of the 1.8 m bed. The deepest sensor was at 80 cm on the central probe. On the other two probes sensors were put down only to 50 cm. Nevertheless, from examining the individual graphs from each sensor we could determine the soil moisture extraction pattern, and by inference the rooting pattern, as shown in Figure 7.5.

Figure 7.5

FIGURE 7.5 Schematic representation of root distribution in a rockmelon crop as determined by soil water extraction.
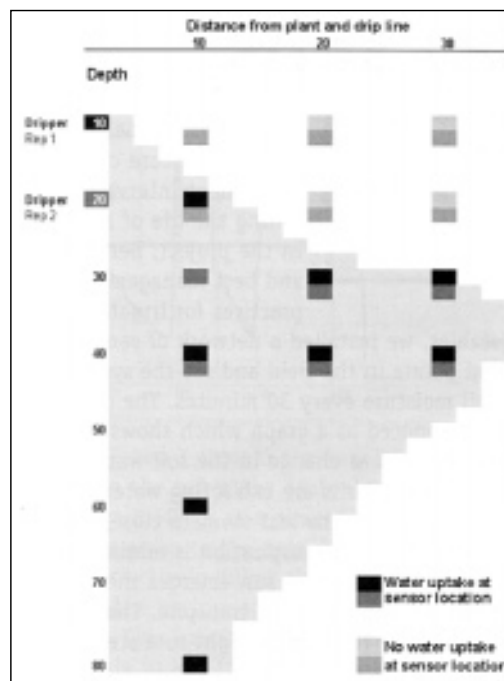
Further results have been obtained from a similar study in Hay where soil is lighter in texture than the Wunamurra Clay. The drip line was buried at 15 cm in the centre of the 1.5 m beds. Probes were installed 10, 30 and 50 cm from the plant row. Sensors were placed down to 80 cm in these probes, with one down to 100 cm in the probe nearest the plant row. Rockmelon roots extracted water at the maximum depth of the sensors, that is, 80 to 100 cm. This occurred when the crop was not irrigated for an extended period, but does show the extent to which roots will explore the soil profile in search of water.

Although roots of the rockmelon grew to 80 to 100 cm in these soils, they may not do so in other soil types. In any case, water extraction was much greater in quantity from around 40 cm, indicating a much greater root density at this depth (Table 8.1). And it is not necessarily efficient for plant growth to be 'forcing' the roots to grow to greater depths. With furrow irrigation it has been regarded as beneficial to make roots grow deep and explore a greater volume of soil, thereby reducing the number of irrigations and hence the number of waterlogging events. However, with sub-surface drip irrigation, such 'benefits' are not so important.

Table 7.1

TABLE 7.1 Decreases in soil water content (mm) over a two-day period, reflecting the uptake of water by roots across the soil profile.

Depth (cm)	Distance (cm)		
	10	20	30
10	–	0	0
20	4	0	0
30	–	2	2
40	10	3	2
60	6	–	–
80	5	–	–

Scheduling irrigation

The irrigator will want to place soil moisture sensors strategically within the root system of a crop to determine when to irrigate and for how long. For rockmelons on self-mulching clay soils these studies indicate that a sensor (capacitance sensor, tensiometer, or gypsum block) should be located between 30 and 50 cm in the profile. When this sensor reading indicates field capacity or full point, then the irrigation system should be shut down.

Ideally a second sensor should be located below the root zone to check that irrigation water is not being lost beyond the extraction zone of crop roots. If this sensor reading increases, then irrigation should be reduced. With rockmelons our results show that after the crop flowers it is unlikely that irrigation water will move beyond the potential root zone in these soils. Nevertheless, a sensor should be located at about 80 cm to check for any drainage and possible leaching.

References
Lovatt J. (1997) *Rockmelons Information Kit*, Agrilink Series. Queensland Department of Primary Industries.
Sanders D.C. (1993) *Vegetable Crop Irrigation*, North Carolina Cooperative Extension Service, North Carolina State University, Raleigh, USA.

Swelling soils: problems
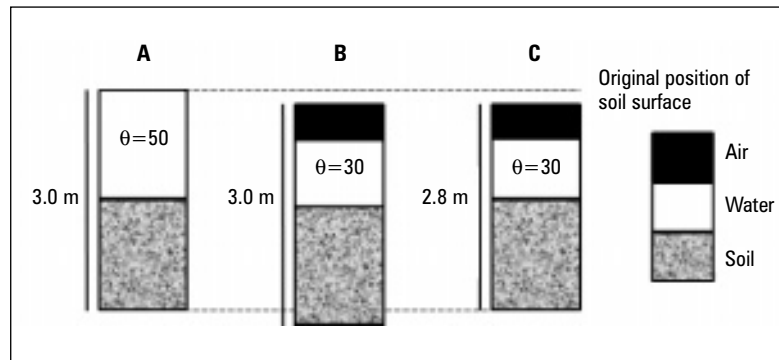with access-tube
installations

SWELLING SOILS: PROBLEMS WITH ACCESS-TUBE INSTALLATIONS

(by Anthony Ringrose-Voase, Zahra Paydar and Hamish Cresswell, CSIRO Land and Water, Canberra ACT)

In the Liverpool Plains in NSW there are extensive areas of clay soils that have significant shrink–swell potential. This case study outlines one of the problems associated with estimating deep drainage in such soils: that of changing soil volume over the wetting and drying cycle.

Figure 7.6

FIGURE 7.6 Representation of moisture-content measurements in a swelling soil when wet and fully swollen (A), dry without correction for height change (B) and dry with correction (C). θ = volumetric water content.

This is manifest as a change in the height of the soil surface relative to a fixed datum.

At 'Hudson' the neutron-probe access tubes have been observed to protrude an extra 20 cm above the soil surface after the soil has been dried by lucerne, compared with a fully wet profile after a long fallow. This phenomenon means it is necessary to correct neutron-probe measurements of profile water to allow for the change of height. This is best illustrated using a simple example (Figure 7.6).

Example
Suppose profile water is measured to a depth of 3 m when the soil profile is at saturation and fully swollen and has an average volumetric moisture content (θ) of 50%, giving a total profile water of 1500 mm (Figure 7.6A). Total profile solid is also 1.5 m. This is called the 'material depth'. Note that the bulk density is 1.325 g/cm^3, assuming a particle density of 2.65 g/cm^3, (2.65 x 1.5 m/3.0 m).

If the same profile was measured after extensive drying by lucerne, for example, it might now have a mean θ of 30%. If this was measured over 3 m depth the calculated profile water would now be 900 mm, giving a change in water storage (ΔS) of 600 mm.

However, if the soil has also shrunk in the process, the height of the surface will have fallen, say, by 0.2 m. Therefore, measuring soil moisture to a depth of 3 m will have included 0.2 m of soil that was not included in the original measurement (Figure 7.6B). Instead, moisture should be measured over only 2.8 m, giving a profile water of 840 mm (Figure 7.6C). That is, the moisture content should be measured over only the depth containing the same material depth of soil. The correct ΔS is therefore 660 mm.

Since ΔS is used to calculate the deep drainage component of the water balance:

Deep drainage = rainfall – evapotranspiration – runoff – ΔS *Equation 1*

then any error in ΔS (60 mm in this example) will be propagated into the deep drainage estimate.

In practice it is difficult to measure the height change to measure the moisture content over the correct depth. Instead, the moisture profile is measured over the full depth and then adjusted by ensuring that the calculated moisture storage refers to a constant material depth. In Figure 7.6C the material depth is the same as in Figure 7.6A (1.5 m). However, because the total volume is smaller, the bulk density has increased to 1.420 g/cm3 (2.65 1.5 m/2.8 m). The bulk density can be used to calculate the depth containing the same material depth:

$$\text{Real depth} = \text{material depth} \; \frac{\text{particle density}}{\text{bulk density}} \qquad \textit{Equation 2}$$

In this example the moisture storage needs to be calculated for a material depth of 1.5 m. This corresponds to a real depth of 1.5 x 2.65 / 1.325 = 3.0 m when wet and 1.5 x 2.65 / 1.420 = 2.8 m when dry. Note that in Figure 7.6B the material depth is 3.0 x 1.420 / 2.65 = 1.61 m.

Figure 7.7

FIGURE 7.7
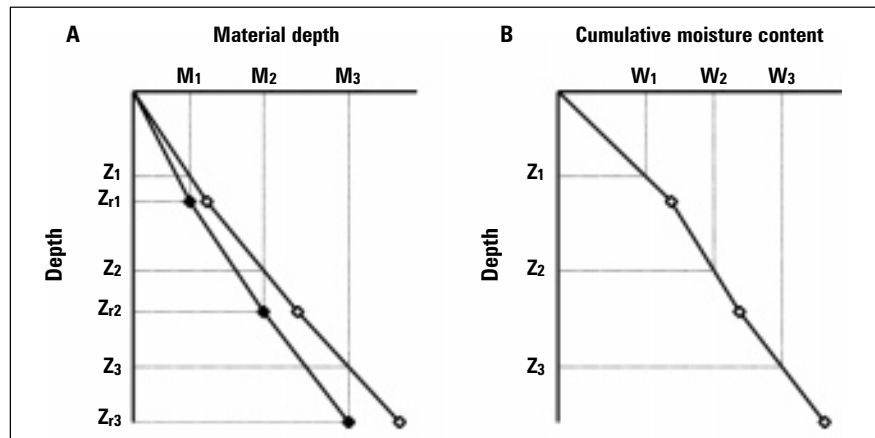
Procedure for correcting moisture contents of three material layers in a swelling soil. A) Sampling layers always have boundaries at depths of Z_{r1}, Z_{r2} and Z_{r3}. The material depths of these boundaries in a fully swollen reference profile (◆) are M_1, M_2, M_3. In a drier profile (◇), the depths corresponding to M_1, M_2, M_3 are Z_1, Z_2 and Z_3. B) shows the cumulative moisture content in the drier soil, with measured points (at depths of Z_{r1}, Z_{r2} and Z_{r3}) shown as ◇. W_1, W_2 and W_3 are the cumulative moisture contents above each material boundary at Z_1, Z_2 and Z_3.

Similar calculations to allow for height change can be used to adjust the moisture contents of each layer in the profile derived from neutron-probe measurements (Figure 7.7). First a fully swollen reference profile is defined as a reference profile. In the reference profile the material layers are defined as corresponding to the measurement layers at depths of Z_{r1}, Z_{r2} and Z_{r3}. The material depths (M_1, M_2 and M_3) at the boundaries between the material/measurement layers are calculated from the bulk densities of overlying layers.

The bulk densities are estimated from the measured moisture contents and a relationship between moisture content and bulk density derived from the samples taken for the neutron probe calibration. As bulk density changes as the soil dries, the locations of the boundaries between material layers move up relative to those between the measurement layers (assuming measurements are made at fixed intervals of, say, 200 mm).

The 'real' depth of the material boundaries can be calculated by interpolating between the material depths of the measurement boundaries (Z_1, Z_2 and Z_3). The cor-

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rect amount of water above the material boundary can then be calculated by interpolating between the cumulative amounts of water above each measurement boundary (W_1, W_2 and W_3).

Figure 7.8 shows the effect of this correction on one of the treatments at 'Hudson'. The correction is of the same order of magnitude as current estimates of deep drainage (e.g. Abbs and Littleboy, 1998).

Figure 7.8

FIGURE 7.8 Estimates of profile water to 3 m depth for one treatment at 'Hudson' before and after correction, together with the actual correction.
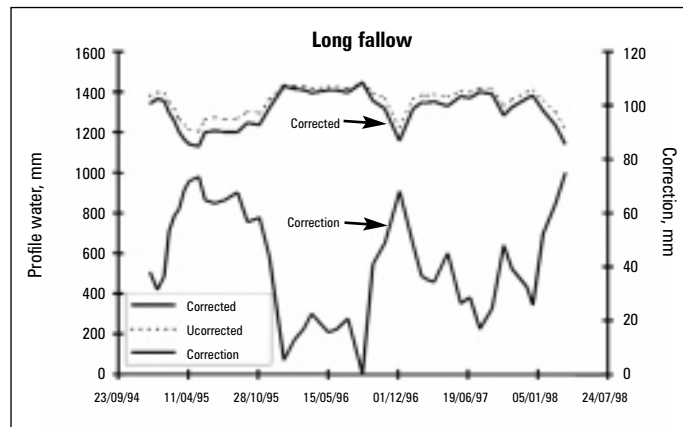
Pitfalls of soil water monitoring: from dam building to damned drippers

PITFALLS OF SOIL WATER MONITORING: FROM DAM BUILDING TO DAMNED DRIPPERS

(by Jan Dearden – Orlando-Wyndham Wines, Rowland Flat.)

Reprinted from *The Australian Grapegrower and Winemaker*, Annual Technical Issue (1998).

This is a case study of both the use of gypsum blocks and some problems with soil water monitoring.

Introduction

Soil water monitoring has been an uncommon practice in the vineyard, and irrigation scheduling has been carried out using various techniques such as by the calendar (every two weeks regardless) or simply by guesswork. Some growers, to be fair, have used a dig stick or shovel to obtain at least some idea of what is happening below the surface. None of these methods is, however, accurate enough to provide the grower with a concise picture of what is happening in and below the root zone. As growers are forced to become more efficient in their water usage there is a growing interest and imperative to monitor more accurately just what is happening to the water once it is applied.

Several soil-water-monitoring systems have become available, and in all cases they measure either soil water content (as a percentage of a volume of soil) or soil water tension (measured in kilopascals).

Soil water content provides an indication of how much water the soil is holding, whereas water tension gives us an indication of how hard the plant has to work to extract the water. The purpose of this article is not, however, to discuss the merits of the various systems but to highlight some of the problems associated with soil water monitoring that have arisen in a project trialling new irrigation strategies using regulated deficit irrigation (RDI).

RDI is an irrigation strategy that imposes controlled periods of water stress on the vine at critical phenological stages in order to manipulate vine and berry growth (Goodwin 1995). The critical factor involved in implementing RDI is the need to monitor soil water status so that we have some idea of whether stress is being applied and, if so, how much.

In this particular trial, automated continuously logging gypsum blocks were installed to monitor soil water status at the five sites. However, the problems encountered would have been the same regardless of the monitoring system, that is, whether the soil water sensors were buried in the soil (TDR) or placed in access tubes such as capacitance neutron probes.
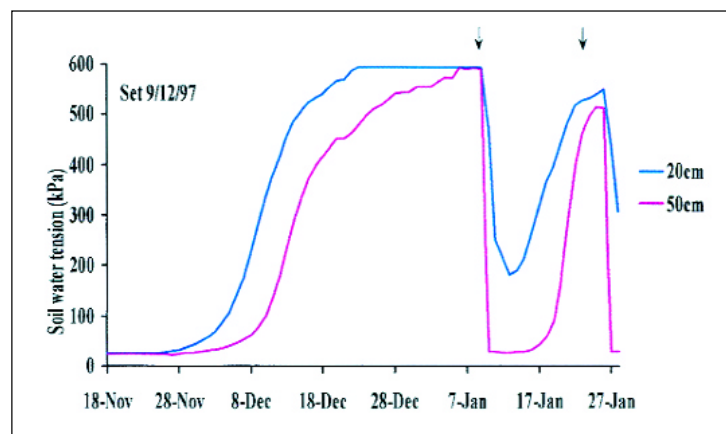
Soil water tension traces

As discussed earlier, gypsum blocks measure soil water tension - in kilopascals (kPa) - and provide an indication of how much work the vine has to do to extract water from the soil.

Figure 7.9 shows a trace obtained over a growing season. At the beginning of the season the soil profile was at field capacity, as demonstrated by the low tension in all four sensors in the root zone. As the vine canopy developed during spring, water use by the plant increased rapidly, and by early January there was very little available water remaining within the root zone (as indicated by the very high tensions experienced).

In this treatment stress was to be imposed for about a month following fruitset and then the vines kept in an unstressed condition until harvest. As can be seen, a period of stress was imposed beginning at set, and then irrigation was applied in mid-January, with an accompanying reduction in tension as the soil profile became wet.

Figure 7.9

FIGURE 7.9 Soil water tension traces (two depths only) obtained from a vineyard during the 1997–98 growing season.

Although these sensors measure soil water content (or soil water tension) and readings are taken at discrete intervals, the data reflect closely those shown in Figure 7.9.

Traces obtained from neutron probes (which monitor soil water content) installed near the sensors reflect reasonably closely the data provided at this station (see Figure 7.10) and, therefore, it is assumed that the traces in Figure 7.9 accurately represent the soil water status at this particular station.

Unfortunately, not all traces obtained were so successful. At each of the sites problems associated with monitoring have arisen, and in each case this has resulted in misleading data. Some of the problems are discussed below. To certain readers some of the issues discussed may seem trite and easily recognised and remedied through routine vineyard maintenance operations. However, when soil water status is being monitored

Figure 7.10

FIGURE 7.10 A neutron-probe trace obtained from sensors positioned in the same row as the gypsum blocks that provided the data in Figure 8.9.
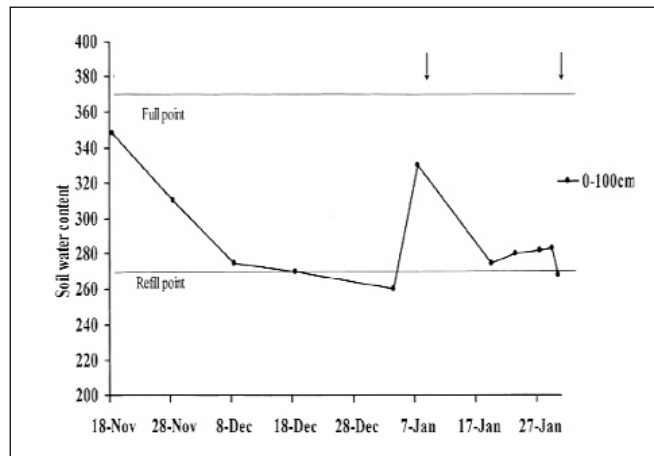
remotely using a modem and computer, vineyard staff are not necessarily attuned to looking for clues associated with the intricacies of soil water monitoring, and the task becomes less simple.

Monitoring problems
### *Water not infiltrating to the sensors*

In several instances the data have displayed continued high soil water tensions after an irrigation. (See Figure 7.11A.) Early in the season, and when the sites were unfamiliar, it was difficult to determine whether the data were meaningful or not. The data may well have been accurate and simply meant that the irrigation amount was insufficient for the water to reach the shallowest sensor. Subsequent field investigations, however, revealed that in many instances the data were erroneous because, for one reason or another, the water was not infiltrating to the sensors.

Figure 7.11

FIGURE 7.11 Soil water traces obtained from two sets of sensors in the same row. (A) The water applied did not infiltrate to the sensors. (B) Here the water infiltrated to the sensors and a response recorded at each irrigation.
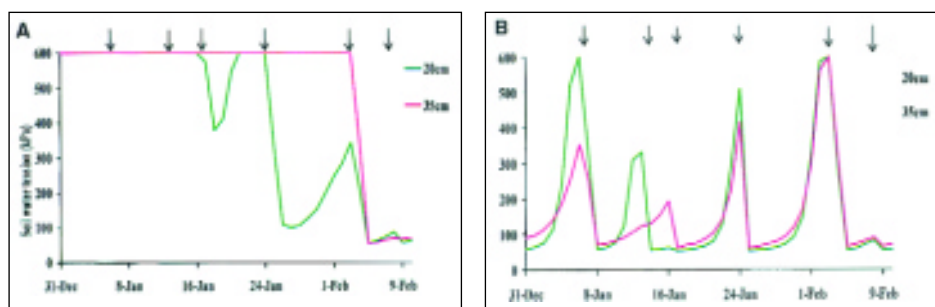
In several cases it was discovered that the water was running into the mid-row region – as was the case in Figure 7.11A – and therefore largely missing the sensors. Figure 7.11B shows a trace obtained from a set of sensors under the same treatment as those in Figure 7.11A. However, in this case, the water actually reached the desired target. At one site the problem was so acute that all three sets of sensors in one treatment failed to respond to irrigation events. The wheel tracks were, however, well watered!

In an attempt to rectify the situation, some ingenious dam building was carried out so that some of the water infiltrated into the soil under the vines. The dramatic effects of this can be seen in Figure 7.11A on February 5. The dam building was certainly

effective, and the root zone was definitely being wetted up, but then the question arose of representative data. Just how representative of the vineyard's soil water status were these data? A stroll down a few of the rows revealed that the problem of water running down into the wheel tracks was widespread, suggesting that the data from the sensors were quite possibly totally misrepresentative. The use of these data to schedule irrigation would have resulted in excessive amounts of water being applied to register a response, and in the process the mid-row area would have become severely water-logged.

Another cause of water not reaching the sensors was the discovery of localised shallow hard pans, which stop water from penetrating to depth. At other sites the sensors had simply been positioned too far away from the emitter. Figure 7.12 shows sets of sensors in the same row. As can be seen, the sensors in 7.12A are well within the wetting zone, while those in 7.12B are on the edge of the wetting zone. The data from these sensors would indicate higher tensions than that actually experienced by the vine.

Figure 7.12

FIGURE 7.12 Two sets of sensors installed in the same row. In (A) (left) the sensors are positioned well within the wetting zone, whereas in (B) (right) the sensors are on the edge of the wetting zone. The corresponding traces indicated misleadingly high tensions.
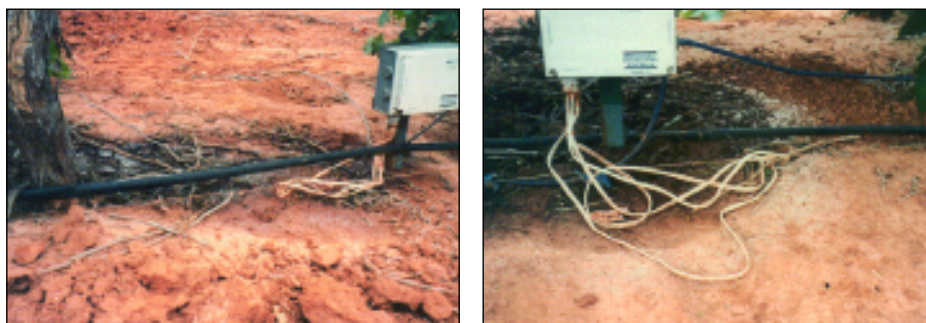
In other instances, blocked emitters have stopped the water from infiltrating to the sensors, and at one site, soil water status data displayed higher tensions than expected because the filtration system had become partly blocked. In other cases the dripline had been severed in a region away from the sensors. Here, obviously, the readings were showing 'dry' because outputs were below specification due to a drop in dripline pressure.

Monitoring equipment not adequately covering the entire root zone

Soil-water monitoring sensors are ideally positioned at several depths within the root zone, and an extra one is installed at the base of the root zone to allow for the monitoring of excessive irrigations and leaching events. However, there have been indications that at some sites in this trial the deepest sensor was not positioned at the base of the root zone but somewhere within it. This means, of course, that part of the root zone was not being monitored and the data obtained were erroneous. Some soil-water monitoring data, for example, indicated that the entire root zone (that is, the region between the shallowest and deepest sensor) was 'dry', and the vines, therefore, were potentially under severe stress. Yet shoot growth was still evident, and there were no signs of stress in the vines. It can only be assumed that these vines were obtaining water from below the region being monitored. In this case it is very difficult to impose controlled periods of stress at the desired phenological stage, because there is no way of knowing the soil water status below the deepest sensor.

Sensors sited on unrepresentative vines

At one site representative vines were selected and sensors installed during winter when the vines were dormant. It was not until the following growing season that it was discovered that two of the sensor sets were installed under diseased vines. In this case the vine being monitored would possibly use less water than healthier vines in the row, thus leading potentially to a situation of over-stressed vines if irrigations were scheduled using the data collected.

Sensors installed under a diseased vine.

Conclusion

CONCLUSION

The major lesson to be learned from these experiences is that soil water monitoring can never become a totally automated or infallible event. Regardless of the type and sophistication of the system used – whether it be one that measures soil water content or one that measures soil water tension, or whether the sensors are placed directly in the soil or within access tubes – there is still a need to observe the vines, look at the positioning of the soil-water monitoring sensors and check driplines and filters. If all those are in order, then give the data some credence, but remember it is simply that: data.

When will I irrigate? Technology to aid irrigation-scheduling decisions on dairy farms

WHEN WILL I IRRIGATE? TECHNOLOGY TO AID IRRIGATION-SCHEDULING DECISIONS ON DAIRY FARMS

(by Mark Wood, Institute for Sustainable Irrigated Agriculture, Tatura, Victoria)

The timing of irrigation applications will significantly affect pasture production. Traditional methods of determining when to irrigate usually involve a degree of uncertainty, especially early and late in the irrigation season and after rain. New instruments that measure the amount of water in soils can give irrigators a better understanding of when pastures are using soil water and how much they are using. These instruments also provide an accurate way of estimating pasture irrigation dates.

Why use new technology?

Environmental concerns about salinity and contaminated runoff and structural changes in the water industry mean that water is becoming a more valuable asset. To ensure that the most is made of each megalitre of water, irrigations should be applied at the correct time.

Applying irrigations at the right time reduces yield losses associated with water-logging and crop water stress. It also reduces the amount of water that runs off a bay or passes below the root zone of pastures. New instrumentation helps to identify the best time to irrigate by measuring how much water is in the soil. The soil water data measured by the new instrumentation also provides an understanding of how much water pastures are using and when they are using it.

Irrigation scheduling system

Aquaflex is one new instrument that measures the amount of water in the soil. It measures the amount of water in the soil by relating the electrical properties of the soil to the water content. The Aquaflex is being tested on a number of dairy farms in northern Victoria to determine whether the technology can help irrigators to decide when to irrigate pastures.

Figure 8.13 shows the complete irrigation-scheduling system. The system consists of:

> Aquaflex: this takes measurements of soil water content
> control box: this stores the data that is measured by the Aquaflex
> modem: this transfers the soil-water-content data back to a computer in the home or dairy via a telephone or radio link
> computer and software: these use the soil water data for decision making.

Figure 7.13

FIGURE 7.13 A schematic diagram of the irrigationscheduling system.
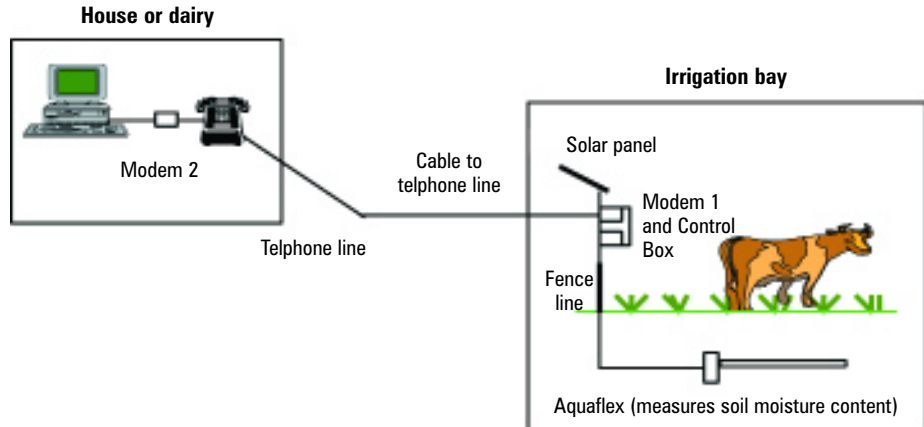
By setting up the above system at five field sites during the 1995–96 irrigation season, we were able to test the equipment and to gauge farmer reaction to the system. Two sites performed poorly due to installation problems. The sites at Dookie College (managed by Geoff Wilhelm), Tragowel (owned by Max and Allan Pleasance) and Tongala (owned by Peter and Judy Fitzgerald) produced good results, with positive responses coming from the irrigators concerned.

Output of the irrigation scheduling system

The Aquaflex takes a reading of the amount of water in the soil every hour. When the measurements are plotted they produce a curve like the one shown in Figure 7.14. Figure 7.14 also includes the irrigation and rainfall events that occurred during the period shown.

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Figure 7.14

FIGURE 7.14 Soil water data from the Dookie College dairy farm. The measurements are from an Aquaflex unit placed at a depth of 400 mm.
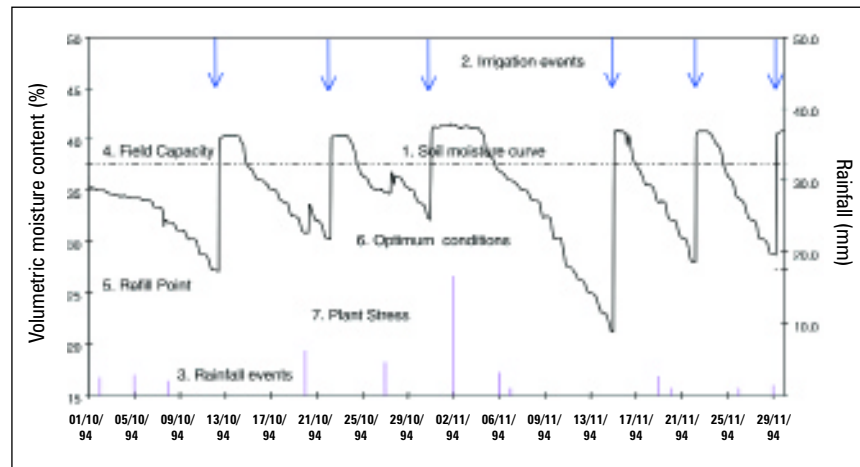
The main features of interest in Figure 7.14 are:

> **1. Soil water curve.** This is a graphical record of the amount of water in the soil. The lefthand axis of the plot is the scale for this curve. The step-like patterns on the curve are a result of plants using water during the day and not at night.

> **2. Irrigation events.** The arrows at the top of the plot indicate irrigation events.

> **3. Rainfall events.** The bars rising from the horizontal axis of the plot show the timing and magnitude of these events. The righthand axis of the plot provides the scale for the rainfall events. The plot shows that rainfall less than 5 mm had little effect on the amount of water in the soil at a depth of 400 mm.

> **4, 5 and 6. Field capacity and refill point.** In the region between these two lines soil conditions are at an optimum for pasture growth, with neither oxygen nor water availability restricting growth.

> **7. The region where pasture stress will occur.** If the amount of water in the soil falls below the refill-point line (4), then the pasture must work harder to remove water from the soil, and growth will be slower.

How to use the information

The information provided by the irrigation scheduling system is most useful during periods when irrigators are uncertain about when to apply water. It is usually difficult to know when to irrigate at the beginning and end of an irrigation season, when the weather is unstable, and at times after rain. Using the irrigation scheduling system, an irrigator can identify when to apply the next irrigation by finding the date where the soil water curve crosses the refill point line.

Of course, most irrigators in northern Victoria need to be able to identify the irrigation date four days in advance to enable them to order the required water. The best methods for estimating soil water content four days in advance are still being investigated. Once familiar with the system, however, users become confident at predicting the next irrigation date.

During peak watering periods when irrigators are watering at a set interval there is less scope to use the system. Despite this, using the information to identify the irrigation interval and to gain knowledge of how much water the pasture is using is helpful to irrigators. Also, when it rains the system indicates how effective the rain has been in replenishing soil water. This information allows the next irrigation to be rescheduled.

Conclusion

The technologies required to help irrigators with their irrigation timing decisions are a reality today. The problem is identifying the technology that suits a given situation and how to best use it. Farm owners and managers have been an integral part of this process. Dairy farms have been the target of the system described in this article and the technology is providing positive results that indicate the system will have an effect on improving water use efficiency on farms.

Note. The Aquaflex is not the only instrument available on the market for measuring soil water. The Aquaflex is being used in this project because of its suitability for monitoring flood irrigated pastures.

Field use of TDR and tensiometers

FIELD USE OF TDR AND TENSIOMETERS

(by P. Charlesworth – CSIRO Land and water, Townsville)

In 1998 a subsurface, drip irrigated rockmelon trial was performed at CSIRO Land and Water, Griffith. Instruments used to evaluate the performance of the irrigation system included a Tektronix TDR system and tensiometers. With careful irrigation management the trial produced double the water use efficiency, on a tonnes/ML basis, than a nearby furrow irrigated crop. Some of the data is presented in Figure 7.15.

Considerable difficulty was experienced with the TDR, with high attenuation of the signal by the soil. The problem was evident only in probes at the 30 to 40 cm depth, which coincided with the highest clay-content layer of the profile. For this reason the shortest probes were used (10 cm).

The tensiometer gave consistent results, and if the readings had coincided with the irrigation peaks values closer to 0 kPa would have been seen.

Figure 7.15

FIGURE 7.15 Comparison of instruments installed in the CSIRO subsurface drip irrigation trial (data from Dr R. Stirzaker, CSIRO Land and Water, Canberra).
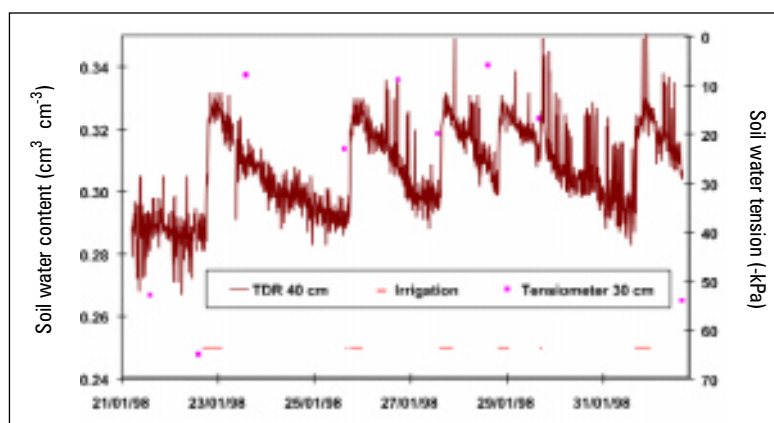
Tensiometer scheduling performance

TENSIOMETER SCHEDULING PERFORMANCE

(by P. Charlesworth – CSIRO Land and water, Townsville)

The following case study demonstrates the use of tensiometers to schedule the same rockmelon crop grown in the previous case study. The data are also good examples of the spatial variability issue raised earlier in these case studies.

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Irrigation scheduling was performed with reference to six tensiometers placed in similar positions in relation to a buried drip irrigation pipe in six different beds.

To present this data, three soil-suction brackets were selected relative to their implication for plant stress :

> 1. WET: < 10 kPa = no irrigation needed.
> 2. GOOD: 10 kPa to 39 kPa = irrigate tomorrow.
> 3. DRY: > 40 kPa = irrigation required yesterday.

The following graph (Figure 7.16) shows the number of tensiometers in each bracket for a given day. For instance, the trial began with six WET tensiometers. These progressively dried until 23 January 1998, when all were DRY. The beds were then irrigated, bringing four tensiometers up to WET, with two remaining DRY.

Figure 7.16

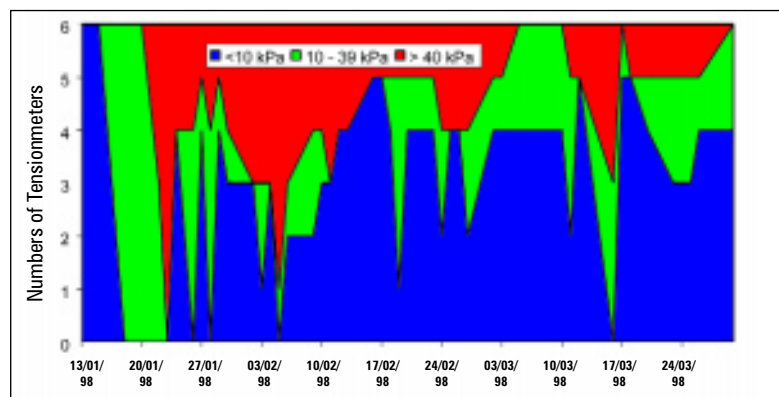**FIGURE 7.16 Rockmelon trial: number of tensiometers in each tension bracket.**

Figure 7.16 demonstrates the problem a producer faces with spatial variability when scheduling a whole field. While the aim was to maintain all tensiometers in the 'GOOD' range, one can see that out of 77 days the aim was met on two days (19 to 21 February). Variations in soil, installation, blocked drippers and plant condition can all contribute to the range of values measured and make the problem of spatial non-homogeneity very hard to deal with. The most common solution would be to irrigate to keep the driest tensiometer in the right range, thus causing over-irrigation in other parts of the field but not risking yield decline.

The value of continuous data for implementing effective and efficient irrigation management

THE VALUE OF CONTINUOUS DATA FOR IMPLEMENTING EFFECTIVE AND EFFICIENT IRRIGATION MANAGEMENT

(by Nigel Robinson, Chief Executive Officer, Agrilink, Adelaide, SA)

Overview
This case study demonstrates the value of using continuous data to implement effective and efficient irrigation management by comparing two sets of data from irrigated vineyards in McLaren Vale and Mildura in southern Australia. The data from McLaren Vale show an effective irrigation schedule where irrigations match crop water use and soil type. The data from Mildura show how a grower used continuous data to implement a major change in irrigation management practices.

When both weather and soil moisture data are available from a site, it is possible to interpret crop water use data with a much higher level of certainty when you are making irrigation management decisions.

Figure 7.17

FIGURE 7.17 McLaren Vale separate graph
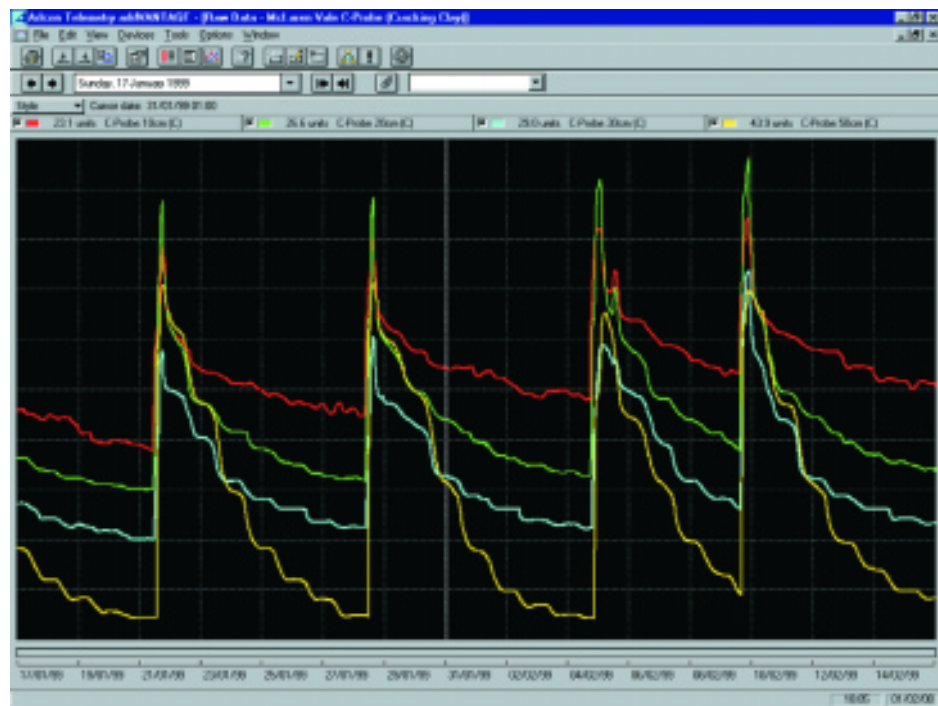
Figure 7.18

FIGURE 7.18 McLaren Vale summed graph
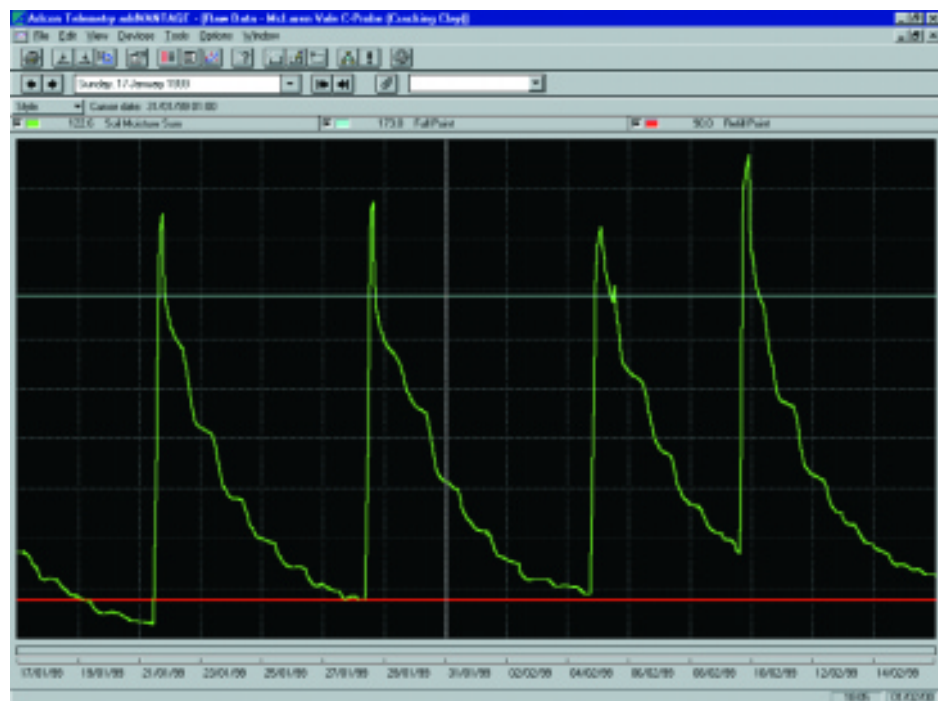
In the sample data sets the weather conditions were relatively uniform. The data have been selected to highlight the major differences between the McLaren Vale and Mildura sites in the use of continuous data for matching the irrigation applied to the crops, the water use and the soil type effectively.

Figure 7.17 shows a separate level graph from a 10-year-old vineyard in the McLaren Vale that was established on a cracking clay soil. The data from each C-Probe sensor at 10, 20, 30 and 50 cm have been plotted over time for 30 days. Irrigations are seen as increases in soil moisture content, with a rapid drop-off after each irrigation peak showing the drainage and crop water use. The daily staircase evident after each irrigation shows the day and night water use of the crop.

When you view the separate level graph, the data from each sensor can either be stacked by sensor depth, showing the readings from the top sensor through to the bottom sensor, or shown on a common 'Y' axis where the wettest sensor appears as the highest sensor and the drier sensors are shown below. In this case, the sensors have been stacked by sensor depth.

You can see that, at a certain soil moisture level at each sensor depth, the crop water use at all levels flattens out. This is the point at which irrigation is applied. If you know the grower's objectives, understand how the crop uses soil moisture at each depth, and have other site-specific data to hand, then you can work out an irrigation schedule. This can be seen in Figure 7.18.

Figure 7.18 shows the summed graph from the same site. Markers on the graph show that an upper limit, or full point, and a lower limit, or refill point, have been set. When the data are assessed, it becomes clear that the grower is running a reasonably tight irrigation schedule. The amount of irrigation applied has been used by the crop at each sensor depth, and irrigation has been reapplied when the water use has stopped at the 50 cm depth. Once the 'overs' and 'unders' have been eliminated, the grower can then focus on more advanced irrigation management practices to manipulate the crop. Extra markers are inserted on the graph to target a change in irrigation to control vegetative growth or the lead into berry set, veraison or harvest.

Figure 7.19 shows a C-Probe separate level graph from a three-year-old vineyard in the Merbein region of Mildura. On this site, the vineyard was established on a heavy clay over a compacted clay layer that comes in just under 50 cm. Again, data can be seen from each sensor at 10, 20, 30 and 50 cm, plotted over time for ninety days. You can see that, after each irrigation peak, there is a period when the sensor values are flat: this indicates waterlogging for a period of time before a daily water use staircase becomes evident. While the daily staircase can be seen at 10, 20 and 30 cm, it is not until the period from 21/02/99 to 27/02/99 that we see the staircase begin at fifty centimetres. We see that a major change occurs from 11/03/99 to 17/03/99, with the soil moisture content at fifty centimetres dropping away.

Before 15 February 1999 the amount of irrigation and the timing of irrigation are too close together, creating waterlogging at 20 and 30 cm and maintaining a watertable at 50 cm. From 15/02/99 onwards, the irrigation interval has been increased and the run time reduced. This has eliminated waterlogging at 20 and 30 cm. On 21 February 1999 the watertable begins to drop away, and crop water use in terms of a daily staircase can be seen at 50 cm. By 17 March 1999 the new irrigation practice has caused the watertable to drop away with irrigation, and irrigation and crop water use are maintained in the top 50 cm.

Figure 7.20 shows the summed graph from the same site in Merbein. The graph highlights the dramatic change that has occurred following the change in irrigation practices. Up until 15/02/99 it is clear that most of the irrigations are too close together

Figure 7.19

FIGURE 7.19 Mildura separate graph
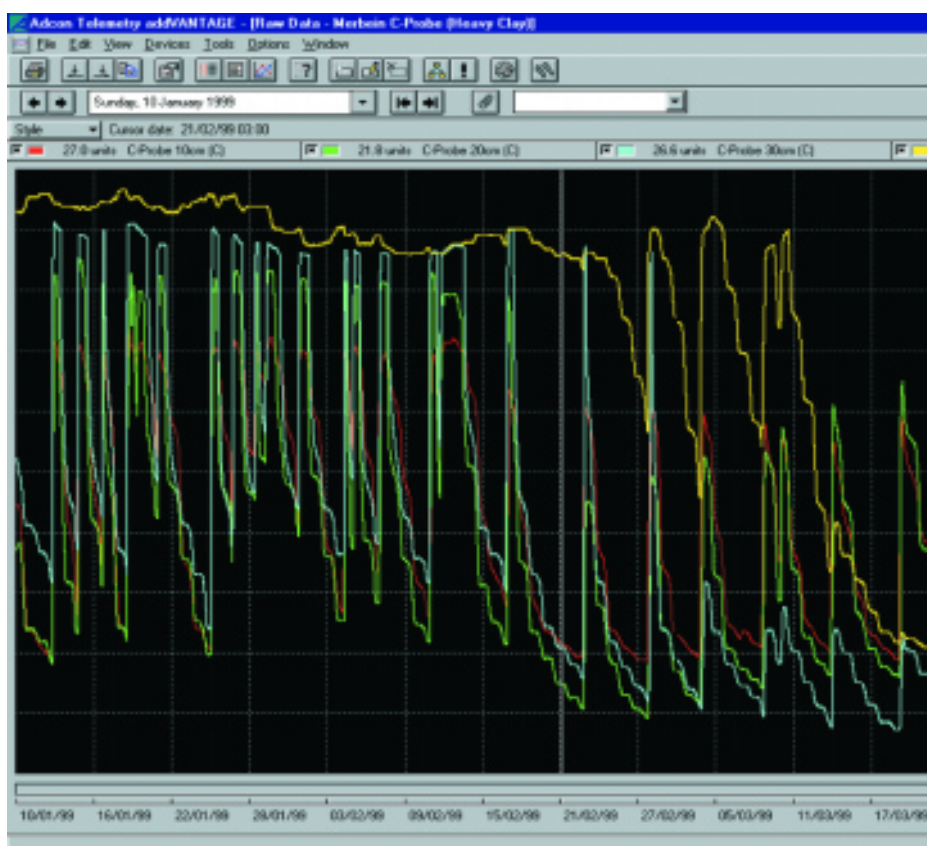
Figure 7.20

FIGURE 7.20 Mildura summed graph

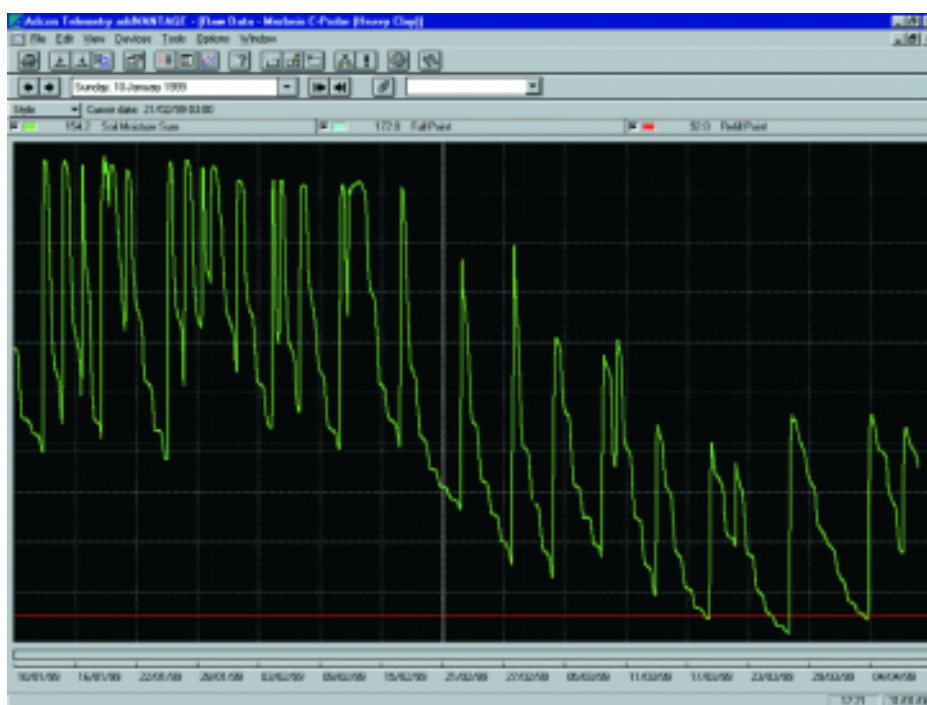and are followed by a large amount of drainage, with waterlogging and limited daily water use evident after each irrigation. After the change in irrigation timing on 15/02/99 the overall soil moisture content drops away. By 17/3/99 a new irrigation schedule has been implemented. It has eliminated waterlogging and has substantially reduced drainage, with strong daily crop water use and a lower overall soil moisture content evident.

In a nutshell, the irrigation schedule before 15/02/99 was 'too much too often', with the grower operating at a refill point which, under the new irrigation schedule, is now his full point. The dramatic change occurred because of the availability of continuous data, which enabled the grower to visualise and understand his crop's water use and soil water relationships.

Before and after: the value of continuous data

Before installing C-Probes and an Adcon Telemetry network, the grower in Mildura had used point data from tensiometers and gypsum blocks along with regular digging to assess soil moisture conditions, but he had experienced great difficulties with waterlogging, salinity and crop loss.

After collecting continuous data and developing confidence in the data, the grower undertook a major change in his irrigation practices that enabled him to reduce his water use and worry significantly. The reduction in irrigation dealt with issues of waterlogging in the root zone as a stepping stone to dealing with salinity issues on site. Significant improvements in crop performance resulted, with limited crop loss.

Having eliminated the overs and unders by getting the timing and amount of irrigation to match the crop water use and soil type, the grower put the basics of irrigation management into place. As a result, the grower now has the confidence to begin a staged introduction of more advanced irrigation management techniques that will achieve the yield and quality objectives sought by winemakers and corporate groups.

The value of continuous data lies in growers being able to implement irrigation management practices that are much more effective and efficient with regard to economic and environmental sustainability.

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9. Web resources and further reading

Web resources

WEB RESOURCES

http://www.microirrigationforum.com/new/sensors/

http://www.sowacs.com

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Appendix 1

PRICELIST FOR ADDIT C-PROBE SOIL MOISTURE SYSTEM

Each C-Probe is connected to an Adcon addIT mini-transceiver. Data are sent via telemetry to the network base station (up to 5 km distance, depending upon terrain). Each addIT can have up to six analogue sensors connected to it. This can be a C-Probe with between one and six sensors and a combination of Adcon weather sensors, depending upon the grower requirements. Detailed below are the most common configurations offered by Agrilink.

Adcon A720 addIT	3 sensor C-Probe	6 sensor C-Probe	3 sensor C-Probe and weather sensor
— Radio telemetry	✔	✔	✔
— Data storage and transmission unit	✔	✔	✔
— Solar power/battery backup	✔	✔	✔
— Support mast	✔	✔	✔
	$1,300	$1,300	$1,300
C-Probe			
— 3 capacitance sensors	✔	–	✔
— 6 capacitance sensors	–	✔	–
— 1.0 m probe length	✔	✔	✔
— addIT junction box	✔	✔	✔
	$1,100	$1,700	$1,100
Weather sensors			
— Rain gauge	–	–	475
— Combisensor (temperature, humidity, leaf wetness)	–	–	1,600
— Sensor interfaces		–	160
	–	–	$2,235
Total	**$2,400**	**$3,000**	**$4,635**

The prices shown above are the cost of the hardware components only and may not include GST. Software, installation, training and network charges may be applicable.

Adcon -Agrilink Network Options

ADCON -AGRILINK NETWORK OPTIONS

Data from all Adcon weather stations are transmitted via telemetry to a local base station. The data are then downloaded to a personal computer that has the Adcon addVANTAGE software running. The base station can be owned and operated by the individual grower, or the data can be transmitted to the local network that is owned and operated by Agrilink.

If the grower elects to have their data transmitted to a local base station, Agrilink downloads the data from the base station on an hourly basis to a server located in the Agrilink office in Adelaide. Growers can then retrieve their data on demand via a 1 800 Freecall using the Adcon addVANTAGE software.

Option A: Grower-owned base station

Adcon hardware cost

–Receiver	✔
–Antenna	✔
	$4,500

Network monitoring (per annum)

—Network monitoring service (per annum) Includes daily monitoring of network to ensure data integrity On-going telephone support by Agrilink technical staff	$500

Option B: Agrilink-owned base station

Maintenance, support and access charges (per annum)	C-Probes	Weather station	C-Probes and weather station
—C-Probe bi-annual maintenance visit (per probe per annum)	$100	–	$100
—Agrilink network data access 24-hour access to data via local weather network using 1800 Freecall telephone number Annual visit to archive database on customer's computer On-going telephone support by Agrilink technical staff	$228	$228	$228
—Annual maintenance and support (per annum) Includes four (4) cleaning and maintenance visits per year Annual visit to calibrate / recalibrate sensors	–	$672	$672

Appendix 2

Time-domain reflectometry: an introduction

(by Robert Edis[1] and Brendan George[2])

INTRODUCTION

Time-domain reflectometry (TDR) has been used in various cable industries for decades to locate the position along a cable at which a break or other damage has occurred. The approach was based on sending an electromagnetic wave pulse along the cable in question, and 'looking' for an echo to be reflected back. Part of the pulse will be reflected wherever the pulse meets a partial 'interface', such as some damage or a crossed wire. The entire pulse may be reflected should it meet a complete interface with a non-conducting material, such as in the case of a break. Knowing the speed at which the pulse moved through the cable, and the timing of the reflected pulse(s), allowed the operator to calculate where to look for a problem.

This application is also used in counter-surveillance activities to find where taps might have been placed on telecommunication conduits (a big problem in the cloak-and-dagger world of soil espionage). This relies upon an unauthorised wire attached to a cable causing a partial reflection of a pulse.

So, if we know the speed at which a pulse travels along a cable, we can measure the travel-time of the pulse to get to the end and back (using an oscilloscope), and thereby calculate the distance the pulse travelled. Conversely, if we know the distance over which the pulse travelled, the travel-time tells us the speed at which the pulse travelled and therefore something about the properties of the conducting material.

The key property that influences the speed of conduct of an electromagnetic wave through a material is the dielectric constant (κ) of that material. When an electric field or electromagnetic signal is imposed on a material, a partial displacement of electrons occurs within the atoms and molecules of the material. The molecules of polar liquids will also become aligned with the field. The dielectric of a medium is a measure of how much an electric field is reduced (relative to a vacuum) by these polarisation effects. With increasing dielectric constant, not only is the electric field reduced, but the velocity of propagation of an electromagnetic signal is also reduced. That is, the higher the dielectric constant, the slower a pulse will travel through that medium. The velocity (v) of the propagation is inversely proportional to the square root of the dielectric constant (κ):

$$v = \frac{c}{\sqrt{\kappa}}$$

Equation 1

where c is the speed of light.

Therefore, if we know the velocity of a pulse, we can calculate the bulk dielectric constant. Because water molecules are dipolar and mostly unbound, they readily twist to align with electromagnetic fields. Therefore water has a high dielectric constant (80.4 at 20ºC, 78.5 at 25ºC, *κ is unitless as it is a ratio of energies*). Molecules in soil solids are mostly fixed, so the solids have a low dielectric constant (between 3 and 5). The dielectric of air is effectively 1. Metals and magnetic materials have very high values for the

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dielectric constant. So, in soil that contains no magnetic or metallic components, water dominates the value of the dielectric constant: the more water, the closer to the value for water. All we need to do is to send a pulse a known distance into the soil and back again, and measure the time between sending the pulse and receiving the reflection.

The adaptation of the time-domain reflectometry (TDR) technique for soil moisture measurement occurred in the late 1970s with the seminal work of Topp, Davis and Annan, published in 1980. This research linked the measured travel time of an electromagnetic wave with the volumetric moisture content (θv, m^3/m^3) of different soil. The relationship, a third-order polynomial, is still the most widely used calibration for conversion of the measured apparent dielectric to estimated θv.

The time-domain reflectometry (TDR) technique is based on the reflection of a fast rise-time voltage pulse generated in either a step-wave or impulse formation. Essentially, the travel time of the EM wave along probes buried in the porous media is measured and the κ calculated. The κ is then related to θv, either empirically or via various physically based mixing models. Instruments may be adapted cable testers or dedicated instruments operating in a portable or stationary capacity.

Principles of TDR

PRINCIPLES OF TDR

A waveform in the transverse electromagnetic mode (TEM) is generated and propagated via a shielded extension cable to an unshielded guide (called a wave guide or probe) of known length embedded in the soil. At the end of the probe the wave is reflected due to the high impedance and returns to the TDR instrument. The phase velocity (v_p) of a TEM in a medium is related to the apparent dielectric and magnetic permeability (μ H m^{-1}) by the equation:

$$v_\rho = \frac{1}{\sqrt{(\kappa\mu)}}\, c_o \qquad\qquad \text{Equation 2}$$

Where c_o is the velocity of the EM wave in a vacuum (free space). The μ (4π x 10^{-7} H m^{-1} in a vacuum) of the soil usually equals unity and the loss factor is thus neglected. The travel time of the TEM wave along the probes (of length L) is simplified:

$$t = \frac{2L}{v} \qquad\qquad \text{Equation 3}$$

If there is negligible loss then Equation 3 with rearrangement simplifies to:

$$\kappa = \left[\frac{c\Delta t}{2L}\right]^2 \qquad\qquad \text{Equation 4}$$

This equation is fundamental to the TDR technique and dielectric determination in porous media. Note that either L or $2L$ is used in this equation, depending on the software of the TDR system. Some systems, such as TRASE TDR automatically consider the travel length 'down and back' along the probes (Soilmoisture Equipment Corporation 1993). If soil is saturated, the travel time of the EM wave along the probes is prolonged and the calculated κ is high. If the soil is dry, the travel time along the probes is short and the κ is therefore low.

EQUIPMENT

1. One TDR unit, consisting of a modified cable tester with an impedance-matching transformer connected to a parallel rod wave connector. (Triple-rod wave guides do not require a balance transformer.) We use a Tectronix 1502b cable tester modified with a RS232 interface. This is a simple addition, though the interface switches probably need changing.
2. Wave guides consisting of matching pairs or triplets (depending on the TDR system) of 5 to 6.35 mm diameter stainless steel rods with lengths between 0.1 to 0.6 m. We use triplets of various lengths.
3. One installation implement and drop hammer for installing the rods in the soil, if needed.
4. One alignment guide for maintaining the rods parallel when inserting them in the soil and an extracting device for retrieving the rods after measurements are taken. We have taken to fixing the cable to the three rods and encasing the join in resin.
5. One 12-volt rechargeable external battery with power cable and fuse as specified by the manufacturer.
6. A battery charger for internal and external 12-volt batteries that are used with the TDR unit.
7. Steel core sampling equipment as specified for the neutron probe, for use whenever the TDR measurements of κ require calibrating against θv, by a field core sampling procedure. This is not really a necessity, as the universal calibration generally holds.
8. Some way of analysing the trace (we use a computer, with TDR software supplied free of charge from HortResearch, Palmerston North, NZ (for a DOS program), or from Utah State University's Soil Physics Group (http://psb.usu.edu/wintdr98/index.html) for a Windows program. Commercial ready-to-go TDR units, of course, have their own software.
9. Optional multiplexing unit and power supply.

PROCEDURE

The details of the procedure for initiating and obtaining a TDR reading of the trace displayed on the oscilloscope depend on the software provided, either with a microprocessor inside the TDR unit or separately with a laptop computer connected to the unit. Two modes of operation are used. The manual mode is used first to introduce the voltage pulses that the unit uses to produce the graph or 'trace' of voltage *vs* time, and secondly to adjust and scale a 'capture window'.

The 'capture window' is for isolating that portion of the trace that is used to determine the travel time 't' of the voltage pulses within the parallel steel rods that comprise the wave guide. With TDR units using three parallel rods as wave guides, the automatic mode may then determine t, κ and θv directly, provided the appropriate calibrations of wave guide and κ versus θv have been entered in the software programme. With TDR units using two parallel rods as wave guides, the 'zero set time' (or time to the start of the wave guides) is set manually, and the 'time to point of reflection' (time to the end of the wave guides) is read automatically to determine the travel time t from which the software calculates κ. The software then refers the value of κ to a calibration of κ versus θv to determine θv.

Both types of TDR systems also provide for independent measurement of the travel time 't' using the manual mode, because the software in automatic mode cannot always cope with the range of possible TDR traces. Hence it is essential for the operator to be able to view the trace and verify the analysis obtained from the automatic mode.

Most of the electric field intensity associated with the voltage pulses in the wave guide is located in the medium, that is, the soil, water or air, immediately next to the

metal rods. Consequently, θv determinations derived from TDR measurements require that good contact always be maintained between the soil and metal surfaces of the rods. Formation of cracks and air gaps around the rods, as may occur when the rods are inserted in hard dry soil, or when they are left in the ground and the soil dries, can pose significant problems. Parallel alignment of the rods that comprise the wave guide is not as critical, but their degree of non-alignment may affect the precision with which the travel time 't' is determined.

Both of the above effects demand that you take care when inserting the rods in the soil and maintaining them parallel. For soil at or near field capacity, rods of 0.15 m or less can be connected directly to the wave guide connector and pushed by hand into the soil. Rods longer than 0.15 m require an alignment guide (item 4 on the equipment list) to keep them parallel as they are pushed into the soil. The alignment guide is then removed within the last 10 cm of insertion so that the bottom surface of the wave guide connector can be pushed firmly against the surface of the soil.

If the soil has too much resistance for you to overcome by hand-pushing, first secure the rods in a separate installation implement and then insert them into the soil through the alignment guide using a drop hammer, as specified in items 3 and 4 on the equipment list. Some models of wave guide connectors may also serve as installation implements for the same procedure. This combined feature has the advantage of facilitating the last stage of rod insertion after you have removed the alignment guide, and of ensuring firm contact between the wave guide connector and the surface of the soil, as described above.

Calibration

CALIBRATION

The travel time read directly from the trace will also include the signal time within the wave guide connector, and very likely other artefacts that are mainly associated with variability in the instrumentation. It is therefore essential to calibrate the parallel-rod wave guide assembly and the TDR unit so that you can determine their measurement characteristics before you insert the rods of the wave guide into the soil. This calibration is done by reading the travel time 't' from the trace, first with the rods in air and then again when they are completely immersed in water in such a way that the bottom surface of the wave guide connector contacts the water surface. The water container should provide ample clearance around the sides and ends of the rods at least equal to the spacing between the rods, and the temperature of the water should be measured.

The dielectric constant of air can be taken as $\kappa_{air} = 1$ and is independent of the temperature. Water at 25°C has a value $\kappa_{water} = 78.54$, which can also be specified to within ± 0.03 % at other temperatures (T°C) by the following relationship:

$$\kappa_{water} = 78.54[1 - 4.579 \times 10^{-3}(T-25) + 1.19 \times 10^{-5}(T-25)^2 - 2.8 \times 10^{-1}(T-25)^3] \ .$$

Equation 5

By knowing the exact values of κ in air and water, and the measured values of the travel times in air and water as read from the trace of the TDR unit, the calibration constants A and B of the instrument for a specified rod length are determined from the relationship:

$$\sqrt{\kappa} = A(t+B)$$

Equation 6

which is the actual working equation that the software uses to calculate the bulk dielectric constant κ of the soil, as described in the 'Pyelab' TDR users guide (Zegelin 1991).

Air and water are nearly ideal dielectric media and serve to calibrate the instrument for obtaining κ. A separate calibration is also needed to derive the θv of the soil from the measured valued of κ. For this purpose a 'universal' calibration relating θv

to κ as measured by TDR was determined by Topp *et al.* (1980) for a wide range of soil textures and porosities in the form of a third order polynomial:

$$\theta v = -5.3 \times 10^{-2} + 2.92 \times 10^{-2}\kappa - 5.5 \times 10^{-4}\kappa^2 + 4.3 \times 10^{-6}\kappa^3.$$

Equation 7

It can be used to determine θv between 0.05 and 0.55 m^3/m^3 from TDR measured values of between 3 and 40. If absolute values of θv are required, then it is best to perform a separate calibration for the particular soil type. The procedure for calibration is the same as for the neutron probe, involving soil core sampling in the same volume of soil that the TDR measurements are taken. However, in irrigation scheduling where it is usually only necessary to monitor changes in water stored within the root depth of the crop, the estimates derived from the 'universal' TDR calibration are acceptable.

The universal calibration predicted the θv ($\pm$0.025 m^3/m^3) from measured κ for mineral soil between 10ºC < T < 36ºC for the range of moisture contents 0 < θv < 0.55 m^3/m^3 with a variation in ρ_b from 1.14 to 1.44 Mg m^{-3}. This equation still forms the basis of most reported θv by the TDR technique. To account for organic soil, Roth *et al.* (1992) developed Equation 8 and Equation 9 for ferric soil. The ferric soil (Rhodic ferralsols, FAO) contained 18.4% and 18.5% iron, respectively (Roth *et al.* 1992). They concluded that if errors of $\pm$0.015 m^3/m^3 for mineral soil and $\pm$0.035 m^3/m^3 for organic soil are acceptable, then site-specific calibration is unnecessary.

$$\kappa/\theta = 0.994 + 10.51\theta + 88.54\theta^2 + 28.92\theta^3 \text{(organic soil, R}^2 = 0.996, \text{SD} = 2.52)$$

Equation 8

$$\kappa(\theta) = 3.92 - 46.07\theta + 374\theta^2 - 320\theta^3 \text{(ferric soil, R}^2 = 0.987, \text{SD} = 1.59)$$

Equation 9

The empirical relationship $\kappa(\theta)$ is limited by conditions such as dry soil ($\theta < 0.05$) where the κ_{soil} dominates (Zegelin *et al.* 1992) and in other porous media such as grain and ore. Further questions relating heavy soil types and the effect of bound water, especially in Australian conditions, have focused research towards determining a physically based relationship between measured κ and reported θv.

Much effort has been put into developing a physically based calibration for the TDR technique. To date, the ability to use the refractive index (the square root of the apparent dielectric, $\sqrt{\kappa}$) indicates a linear relationship with some change in the coefficients still depending on soil type. A physically based calibration is preferred in determining the $\kappa(\theta v)$ relationship in soil. However, until now, the extra parameters required have deterred most users from employing physically derived mixing models and the use of the refractive index. White *et al.* (1994), though acknowledging the benefit of such an approach, suggest that most physically derived models are in fact 'semi-empirical'. The majority of θv measurements reported by the TDR technique are still determined by the Topp *et al.* (1980) universal empirical Equation 10 or derivatives of it.

Effect of bulk density on TDR calibration

EFFECT OF BULK DENSITY ON TDR CALIBRATION

Particular attention has been focused on the effect of soil bulk density or porosity on the measurement of κ by TDR. An increase in ρ_b may yield a corresponding increase in specific surface area, leading to higher apparent κ. Incorporating ρ_b into their calibration of θv against time, Ledieu *et al.* (1986) showed that a change of 0.1 Mg/m3 caused a variation of 0.0034 m^3/m^3 in reported ρ_b. Jacobsen and Schjonning (1993a) included ρ_b, clay content and organic matter content in a third-order polynomial equation (Equation 10) from their study of five topsoil and subsoil samples. The incorporation of ρb, clay content and organic matter (OM), although significant, improved the fit (adjusted r^2) only marginally from an already very good 0.980 to 0.989.

$$\theta = -3.41\times10^{-2}+3.45\times10^{-2}\kappa-1.14\times10^{-3}\kappa^2+1.71\times10^{-5}\kappa^3-3.70\times10^{-2}\rho_b+$$
$$7.36\times10^{-4}\%clay+4.77\times10^{-3}\%OM$$

Equation 10

A calibration of θv to κ to increase sensitivity to change in ρ_b by normalising with respect to ρ_b gives (Malicki *et al.*, 1996):

$$\theta_{(\kappa,\rho_b)} = \frac{\sqrt{\kappa} - 0.819 - 0.168\rho_b - 0.159\rho_b^2}{7.17 + 1.18\rho_b} \qquad \text{Equation 11}$$

In a field study conducted by Jacobsen and Schjonning (1993b) the authors found that the inclusion of ρ_b did not improve their laboratory calibration equation (Equation 10), concluding that this was due to the small improvement offered versus the uncertainty of measurement.

Bulk soil electrical conductivity (EC) effect on θv measurement

BULK SOIL ELECTRICAL CONDUCTIVITY (EC) EFFECT ON θV MEASUREMENT

The bulk soil electrical conductivity (EC) can affect the determination of θv in two ways. First, there is an increase in the apparent dielectric constant. The TDR technique is then susceptible to over-estimation of the θv as, described by Dalton (1992). Dalton (1992) concluded when *pore-water* reaches 0.8 S m^{-1} over-estimation of θv occurs. Vanclooster *et al.* (1993) suggested that this figure could be 1.0Sm^{-1}. It is likely then, that a large EC calibration will be required. It has been suggested that, to avoid this situation, using short extension cables and shorter probes will help to determine the end-point. To date there is no indicative study of this limitation in Australian soil. Secondly, in highly saline soils, conductivity losses may result in insufficient reflectance for trace interpretation. Clearly the interaction of the EC and κ in relation to dielectric losses is complex and needs to be understood better. However, remember that EM loss can be minimised by generating frequencies between 50 MHz and 10 GHz.

Field operation

FIELD OPERATION

In the field, probes (mainly of stainless steel) are generally of two forms: either balanced (two-wire) or unbalanced (three-wire). Generally, two-wire probes are used for portable measurement, and the three-wire probes are used for permanently placed probes. For a detailed discussion on this see Zegelin *et al.* (1989).

The effective length of the probes (and therefore the depth of measurement) will be determined by the power of the step pulse generated by the TDR, the soil type (heavy clay attenuates the EM wave more than sandier soil types) and the moisture content of the soil (Dalton 1992). Two-metre-long probes have been used successfully to measure moisture content in a gravelly Australian soil (Zegelin *et al.* 1992). However, in wet, heavy clay soil, the probe (wave guide) length has sometimes been reduced to as little as 200 mm. This current problem is being rectified by increasing the power and stability of the EM wave and by coating probes with a thin cover of a low dielectric material (J. Norris, pers. comm., SEC, USA). The aim is to ensure that a percentage of the wave will travel the length of the probes and be reflected, allowing determination of Δt. Coated rods are particularly useful for difficult-to-replace installations and highly saline conditions (for example, in cement).

A practical application of the TDR technique is in irrigation scheduling. The optimum rod lengths and rod diameter for this purpose are specified in item 2 of the equipment list. The rods are held parallel in the wave guide connector or installation implement and inserted vertically into the soil in order to determine the full and refill points for the particular stage of growth and root depth of the crop, as previously described. For longer term monitoring of the changes in water content within the root zone, insert the parallel rods of the wave guide at an angle of 45º off the vertical. This reduces the tendency for initiating cracks and holes, which can act as preferential paths for water during irrigation or rainfall. Alternatively, to determine the moisture

profile, you can install the wave guides horizontally at various depths from a pit. You then backfill the pit, leaving the BNC end of the cable accessible at the surface. The principal advantage of the TDR technique for irrigation scheduling is that you usually do not need to do individual soil profile calibrations involving separate determinations of θv. This advantage allows you to do routine multi-sited monitoring of changes in the amount of water stored, using only the TDR measurements of κ and the 'universal' calibration of θv versus κ.

When used in conjunction with a multiplexer, a single TDR unit can be used to monitor a number of wave guide locations (typically 16). Most TDR software allows the measurement of θv (and σ) at several sites (through the multiplexer), at selected time intervals, with data logging. This is very useful for monitoring dynamic processes such as profile wetting and solute transport.

Another advantage is that the volume that the TDR technique samples is suitably large for most field applications. For dual-rod wave guides, the soil sampled is essentially an elliptical cylinder around the length of the rods. For the triple-rod wave guide, the volume sampled is approximately a right cylinder around the central rod with a radius equal to the spacing (50 mm) between the rods. Nevertheless, good contact should always be maintained between the soil and the metal surfaces of the rods, as emphasised previously.

Other factors that may limit the use of the TDR technique are the large proportion of bound water found in some expansive clay soils, coupled with high surface conduction and sharp breaks in moisture content. Bound water has values of dielectric constant approaching that of the soil solids, to the point where the water contributing to the bulk dielectric constant can no longer be distinguished from that of the solids. Surface-conductive soil limits the rod length that can be used in the wave guide connector by reducing the amplitude of the reflected signal to the point where it can no longer be detected, even though the soil may not necessarily have a high free-salt content. The electric conduction in this case occurs significantly through the ions associated with the electric double layer of the clay particles. Sharp breaks in the soil moisture content along the length of the rods produce 'traces' that may not always be analysable by the software in the automatic mode and must be verified manually. Stony soils offer difficulties for wave guide insertion and, depending on the nature of the stones, for calibration. Extremes in temperature may need to be considered also, and taken into account when you are calibrating the TDR κ value for water. Long-term buried installations sometimes have degraded traces, due to deterioration of the join between the wave guide and the cable. With time, the traces become increasingly difficult to interpret. If the wave guide is buried, the link between the cable and the wave guide should be protected by, for example, encasing it in resin.

TDR for measuring solute concentration

TDR FOR MEASURING SOLUTE CONCENTRATION

Dalton *et al.* (1984) first proposed the use of TDR for measuring the electrical conductivity (σ) of the soil. They demonstrated that the attenuation of a voltage pulse along the probe could be used to deduce σ. This attenuation was used to infer the solute resident concentration (C_r). Since then, several different approaches have been suggested for using the attenuation of the reflected signal to determine σ, and they are based on use of various values of the voltage at different points along the TDR trace. However, so far we still do not know which of the alternative expressions is the most appropriate for the calculation of σ.

It must be remembered that bulk soil electrical conductivity is quite different to the electrical conductivity of the soil solution. Conductance is also influenced by surface charges of minerals and ions in the electric double layer (surface conductance). There is also a strong dependence of electrical conductivity on the moisture content of the soil. As the soil dries, the path lengths of conductivity increase (tortuosity), increasing the resistivity and thereby decreasing the conductivity for the same solution's electri-

cal conductivity. It is conceivable that the conductivity mediated by solids can change if the mineral's surface-electrical properties are changed, such as through pH change or P adsorption. All these factors will then be affected by temperature. These difficulties mean that a universal calibration between bulk electrical conductivity and solution electrical conductivity is unlikely. Nevertheless, the simultaneous measurement of θv and σ has meant that TDR has become a valuable tool in solute-transport studies.

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Appendix 3

Frequency Domain Reflectometry

The following critique is taken from White and Zegelin (1995).

When a potential is placed across the plates of a capacitor containing a dielectric, charges induced by polarisation of the material act to counter the charges imposed on the plates. Ideally, the capacitance between two parallel plates is related to the dielectric constant.

It is assumed that the lateral dimensions of the plate are much larger than the plate spacing and that all other sources of capacitance (C_e) are insignificant. However, these conditions are seldom met.

The presence of electrolytes and mobile surface charges in soils tends, at low measurement frequencies, to produce interfacial polarisation at the electrode surfaces, causing C_e to swamp the contribution by the soil's dielectric constant.

These problems plagued early attempts to use direct measurements of capacitance to determine soil-water content and for a long time discouraged interest in the technique (Gardner 1987). The recognition that interfacial polarisation could be overcome by using measurement frequencies above 50 MHz has renewed interest in the capacitance technique as an effective tool for monitoring *in situ* changes in soil-water content (Thomas 1966). Advances in electronics have permitted the routine use of cheap high frequency circuits in the 50 to 150 MHz range, thus increasing the accessibility of the technique (Dean *et al.* 1987).

MEASUREMENT PRINCIPLES

In recent improvements to the capacitance technique, the capacitor containing the volume of soil to be measured forms part of the feedback loop of an inductance-capacitance resonance circuit of a Colpitts or Clapp high-frequency oscillator (Wobschall 1980, Dean *et al.* 1987). The resonance angular frequency of the oscillator, ω_r, is related to the capacitance of the soil probe, which is in turn related to the dielectric constant of the soil.

PROBE GEOMETRY

The geometry of the parallel plate capacitor is optimal, since almost all the electric field is contained between the plates and the contained field strength distribution varies as the reciprocal of distance from the plate. Such parallel plate probes have been widely used in laboratory determinations of water content of porous materials, particularly samples of stored grains, but their use in the field is less convenient because of plate insertion and soil disturbance problems.

More recently designed capacitance probes use split cylindrical electrodes that can be buried in the soil or positioned at different depths down plastic access tubes embedded in the soil, as shown in Figure A3.1. The oscillator circuit and other electronics are placed within the cylindrical electrode probe (Dean *et al.* 1987).

It is clear from the figure that not all the field between the cylindrical electrodes propagates into the soil. Some also flows through the plastic access tube and through the interior of the probe. The relative amounts of the field penetrating the probe, the access tube and the soil compartments will depend on the radius of the cylindrical electrodes, the gap between the probes and the relative dielectric constants of the compartments. As the radius and gap become smaller, and as the soil becomes wetter, we expect that less of the field will be proportioned to the soil compartment. The dielectric material between the cylindrical electrodes must have a low dielectric constant to ensure an adequate and accurate response to low soil dielectric constant, that is, low soil-water content.

Figure A3.1

FIGURE A3.1. Capacitance probe cylindrical electrodes for use with plastic access tubes.
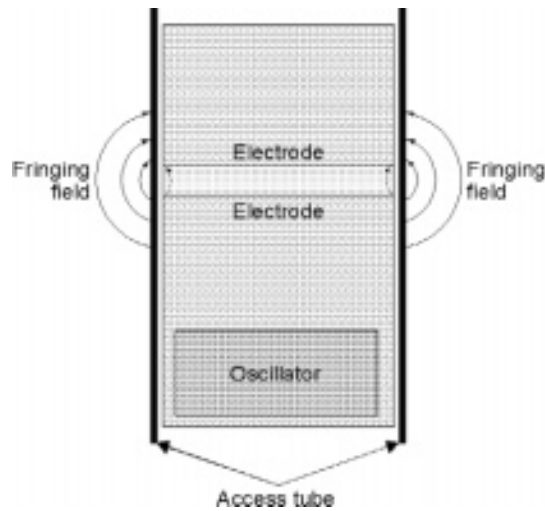
Zone of influence

ZONE OF INFLUENCE

Two critical questions arise concerning any measurement probe placed in a porous material: over what region does the probe measure; and what is the spatial weighting of its response within that region? Dean *et al.* (1987) tried to address those questions for the capacitance probe through an approximate experimental analysis of the region of influence of a probe similar to that in Figure A3.1. It is clear from Figure A3.1 that most of the field strength will be concentrated in the gap region between the plates. In normal use, at least part of this region is occupied by the plastic access tube.

Dean *et al.* (1987) found that the region of influence is indeed restricted to a relatively narrow disc-shaped region surrounding the probe and centred on the gap between the electrodes. The probe is most sensitive to the region immediately adjacent to this gap. This means that the probe is very sensitive to any air gap between the probe, access tube and the soil, and that special care must be exercised in installation (Bell *et al.* 1987). A rigorous analysis of the effect of probe radius, plate gap width, plate width and access tube thickness on the zone of influence and the spatial sensitivity of capacitance probes has yet to be undertaken.

Response to water content changes

RESPONSE TO WATER CONTENT CHANGES

The relationship between the circuit's resonance frequency and the volumetric water content of the clearly shows that as θ increases, there is a non-linear decrease ω_r. Published data do show such a decline in resonance frequency with ω_r decreasing by 29% when the capacitance probe is moved from air to pure water (Bell *et al*. 1987).

Extant calibration curves for different soils have used a very narrow water content range and have assumed that calibration is linear over that range. Somewhat disturbingly, these calibration curves show an almost ninefold variation in slope (Bell *et al.* 1987). This may indicate that the assumed constants in the calibration equation are in practice not constant, or it may be due to the electrical conductivity of the soil, whose effect on the capacitance probe's performance appear not to have been explored systematically. Whatever the reason for the considerable disparity been calibration curves, these differences mean that calibration curves must be constructed for each site.

The stability, sensitivity to temperature change, and repeatability of measurements with the capacitance probe have been examined. It is found that measurement repeatability is better than 0.005 volumetric water content, and sensitivity to small changes in volumetric water content in dry materials is large. This repeatability and sensitivity are part of the strength of the capacitance probe technique.

Appendix 4

Appendix 4

Neutron Moderation Method (NMM)

(by B.H.George, State Forests of NSW, PO Box 100, Beecroft NSW 2119: brendang@sf.nsw.gov.au)

Introduction

INTRODUCTION

The neutron moderation method (NMM) is widely used in soil water measurement studies in Australia and throughout the world. Indeed, as reported in the July 1999 (no. 73) edition of *Wispas* (HortResearch, NZ), the neutron method has finally 'made it' into mainstream science. The technique is indeed well established, and its ubiquitous use is a testimony to those who developed the *in situ* capabilities.

The neutron moderation technique is based on the measurement of fast-moving neutrons that are slowed (thermalised) by an elastic collision with existing hydrogen particles in the soil. Gardner and Kirkham (1952) developed the NMM technique with others such as van Bavel *et al.* (1956), Holmes (1956) and Williams *et al.* (1981).

The high energy, fast-moving neutrons are a product of radioactive decay. Originally the source used was radium–beryllium, however, americium–beryllium is more commonly used today. For example, Campbell Scientific Nuclear use a sealed Am^{241}/Be source of strength 100 mCi (= 3.7 x 10^{-8} Bq). Fast neutrons (> 5 MeV) are expelled from the decaying source following interaction between an alpha emitter (Am^{241}) and Be. The high-energy neutrons travel into the soil matrix, where continued collisions with soil constituent nuclei thermalise the neutrons: that is, the neutron energy dissipates to a level of less than 0.25 eV. The returning thermalised neutrons collide in the detector tube (BF_3), with the boron nuclei emitting an alpha particle that in turn creates a charge that is counted by a scalar. This is related to the ratio of emitted fast neutrons.

The transfer of energy from the emitted fast neutron (where mass is 1.67 x 10^{-21} kg) is greatest when it collides with particles of a similar size. In the soil matrix H^+ is a similar mass yielding elastic collisions with emitted high-energy neutrons. Hydrogen (H^+) is present in the soil as a constituent of soil organic matter, soil clay minerals and water. Water is the only form of H^+ that will change from measurement to measurement. Therefore, any change in the counts recorded by the NMM is due to a change in the water, with an increase in counts relating to an increase in soil water content. Gardner and Kirkham (1952) indicated (their Table 1) that hydrogen, due to its high nuclear cross- section (the probability that the fast neutron will interact with the atom), and increasing scattering cross-section (relative to other atoms present) as the neutrons lost energy, was very efficient in slowing neutrons. Fast neutrons may be 'lost' (captured) to the soil matrix when elements such as fluorine, chlorine, potassium, iron (Lal 1974, Carneiro and de Jong 1985), boron (Wilson 1988) and manganese are present. Other factors that influence the relationship between emission of fast neutrons and soil water content and affect calibration are discussed later.

Considerable refinement of neutron meter design and production has occurred in the last forty-five years. Units are now more portable and electronics more stable. Factors including the effect of source and detector separation (Olgaard and Haahr 1967, Wilson and Ritchie 1986) and temperature stabilisation of electronics have been incorporated in modern neutron meter design.

Methodology

METHODOLOGY

A particular advantage of the NMM technique is its ability to obtain repeated measurements down the soil profile, as shown in Figure A4.1. In the field, aluminium (Carneiro and de Jong 1985) or PVC (Chanasyk and McKenzie 1986) tubes, are insert-

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ed into the soil and stoppered to minimise water entry. They should be installed so that soil compaction is minimised while ensuring reasonable contact with the surrounding soil.

Prebble *et al*. (1981), with data from Shrale (1976) showed that an infinitely long air-gap (greater than > 2 mm) surrounding a 51-mm diameter tube when saturated (say, immediately after irrigation) had a significant impact. However, in field situations with careful installation using a suitably sized auger, air-gaps in excess of > 2 mm should be minimised. Where air gaps are unavoidable, as is occasionally experienced in active shrink-swell clay soil, the addition of sand around access tubes does not improve the measurement of soil water (Cull 1979). Adding a slurry (made from a mixture of bentonite and/or other clay materials and cement) along the access tube is not advisable (< 2 mm). If the slurry is thicker you may be introducing a material with different characteristics to those of the measured soil (Prebble *et al*. 1981).

Figure A4.1.

FIGURE A4.1. An example of a typical soil soil water profile determined by the NMM technique (after Williams *et al.* 1981)
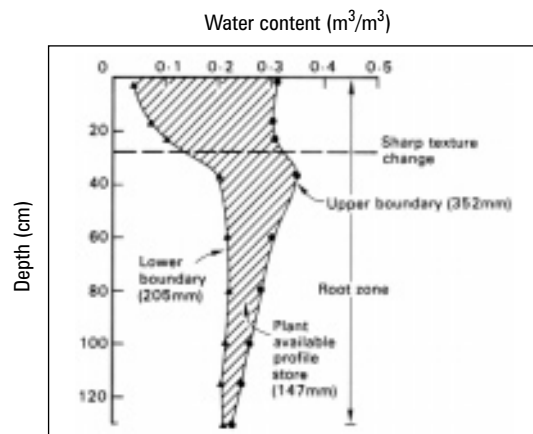
The count time is an important consideration for increasing the instrument precision while reducing the time for measurements. Table A4.1 shows the increase in count time (CPN 503DR probe, 50 readings in a dry sand drum and a water drum; George 1999) and the associated error and precision for two extreme conditions with an NMM.

Figure A4.1.

TABLE A4.1. Influence of NMM count time on the reported raw counts by a CPN Hydroprobe® in a drum filled with water and a drum filled with dry sand.

Count time (seconds)	Mean count	Standard deviation	Standard error of the mean	Range	Coefficient of variation (%)	Precision (% error)
Sand						
1	384.64	68.645	9.708	304	0.178	39.50
4	390.32	35.476	5.017	204	0.091	19.60
16	393.8	19.878	2.811	87	0.050	9.76
32	393.48	15.471	2.188	67	0.039	6.90
64	396.5	9.384	1.327	37	0.024	4.86
Water						
1	36784.0	825.73	116.78	3360	0.022	4.04
4	36673.4	311.542	44.06	1341	0.008	2.02
16	36722.7	198.415	28.06	841	0.005	1.01
32	36737.6	141.995	20.08	672	0.004	0.71
64	36677.0	96.969	13.71	383	0.003	0.51

Readings are taken at depths down the profile with a nominated count time (for example, 16 seconds). Commonly in irrigated production systems three aluminium tubes are then averaged and soil water reported as a single reading. This aims to counter the effect of spatial variability reducing the value of the measured soil water content data (Cull 1979). Readings may be taken with the neutron meter as a raw count or a count relative to a reading in a drum of water or in the instrument shield (Greacen *et al.* 1981). The count ratio is used to minimise potential drift in instrument readings.

Improved stability of electronics and reduced drift in counting mechanisms in the past fifteen years have diminished the importance of this process. However, instruments differ in their stability (O'Leary and Incerti 1993) and regular normalisation in a large (> 200 L) water drum on a monthly or seasonal basis should be carried out.

NMM calibration

NMM CALIBRATION

The need for calibration of the NMM in different porous materials invokes interesting discussion. Neutron meters are commonly provided with (factory) standard calibrations for use in common soil types. In Australia, Cull (1979) established a series of standard calibrations, and currently these calibrations are extensively used in the irrigation industry (P. Cull, pers. comm., Irricrop Technologies International Pty Ltd, Australia).

Other research indicates support for a universal calibration encompassing the difference in neutron scattering due to bulk density and texture (Chanasyk and McKenzie 1986). In irrigated agriculture, in many soil types, farmers who measure changes in soil water content commonly use universal calibrations with reasonable success. Success of the universal calibration in scientific studies is limited, with field studies indicating that other influences present affect soil water determination by the neutron moderation method. Greacen *et al.* (1981) described, in field and laboratory conditions, a calibration procedure for the neutron moisture method in Australian soil.

The major concern is to consider bulk density (ρ_b, Mg m^{-3}) when you are calibrating the NMM in field studies. Holmes (1966) discussed the influence of ρ_b on calibration and postulated that changes in ρ_b affected the macroscopic absorption cross-section (for thermal neutrons). Olgaard and Haahr (1968) disagreed with Holmes (1966), indicating that ρ_b actually influenced the transport cross-sections of fast and slow neutrons. Wilson and Ritchie (1986) used a multi-group neutron diffusion theory to show a linear response of the neutron moisture meter to a change in matrix density and neutron-scattering cross-section.

Comparing *in situ* determination to that in re-packed soil, Carneiro and De Jong (1985) found that a linear relationship yielded a suitable calibration for their soil, a red-yellow Podzolic. However, the findings of Wilson and Ritchie (1986) were different: they indicated that there was a non-linear response of the neutron moisture meter to the thermal neutron-absorption cross-section and the soil water density. The error associated with deriving the water content, indicating the minimum error likely to be achieved (depending on the chemical limitations of the soil description) is ±1.6% to ±3.5% (Wilson 1988).

In many field studies there is scant consideration of these parameters in the calibration of NMM response to soil water content. Most calibrations encompass the errors associated with neutron capture, thermal neutron cross-section and neutron scattering cross-section, and these parameters are usually excluded from discussions. An example of this is the discussion of Carneiro and de Jong (1985), where the authors contend that the difference in slope estimation between two soils is probably due to differences in clay content, Fe and Ti content or ρ_b of re-packed columns.

Field calibration of neutron meters is most commonly carried out with a linear equation (from regression analysis) derived for a particular soil type and/or horizon, in the form of:

$$\theta = a + b \times n$$

Equation **1**

Where θ is the volumetric water content (m³/m³), a is a constant (intercept), b is a constant (slope) and n is the neutron count or neutron count ratio. Greacen *et al*. (1981) indicated that correct regression of the count (ratio) on water content (water content as the independent variable) reduced the possibility of introducing a bias to the calibration.

It is important to consider the soil bulk density, especially in duplex soil where there is potential for significant change in bulk density in the B-horizon. An empirical relationship (Greacen and Shrale 1976) can be used to correct for bulk density effects:

$$n_c = n \times \sqrt{\frac{\rho_s}{\rho}}$$

Equation **2**

Where n_c is the corrected count ratio, n is the count ratio relating to the bulk density (ρ) and ρ_s is the average bulk density for the site calibration. Figure A4.2 (George 1999) shows the effect of including bulk density in comparing the (uncorrected for bulk density) 'universal calibration' supplied by the manufacturer and a local calibration determined in a Brown Chromosol (Isbell 1996).

Figure A4.2.

FIGURE A4.2. Plot of the factory-supplied 'universal calibration' in a Brown Chromosol (left) without accounting for measured bulk density change at the site and (right) including the ratio of the depth-based bulk density with the average site bulk density.
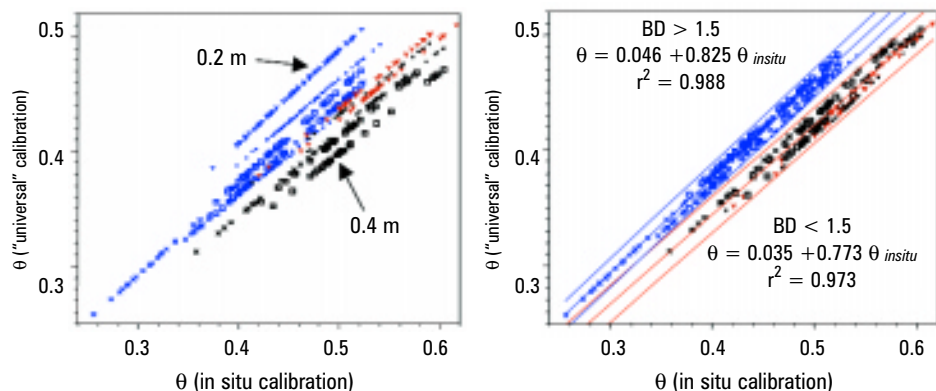
The neutron moisture calibration generally involves taking neutron readings in the extremes of wet (field capacity) and dry soil and relating this to wetness (w). The ρ_b is either calculated or estimated to yield a neutron-moisture content to known water-content relationship. Gravimetric samples can be collected by careful removal of samples during access-tube installation, destructive sampling around access tubes, or sampling from soil near the installed access tubes (Corbeels *et al*. 1999).

A second method of calibration relates the determination of the neutron thermal adsorption and diffusion constants as shown by Vachaud *et al*. (1977). This method is not used extensively for field calibration of the NMM, as the equipment is not readily available and is difficult to use in some field situations.

Data handling and interpretation

DATA HANDLING AND INTERPRETATION

Readings from NMMs can be written down and entered into a computer or stored on the instrument and downloaded to a PC for analysis. Assuming the calibration has been determined, the results can be readily interpreted in a general spreadsheet (such

as Excel) or via dedicated software (for example, Watsked (CSIRO) or 'the Probe'). Information can be readily displayed down the soil profile. (See Figure A4.1.) It can be used to indicate the amount of water available and the activity in the root zone where water is extracted, or to identify temporally the soil water content at nominated depths or an integrated profile soil water content (for example, George and Finch 1995). Figure A4.3 shows the measurement of soil moisture content with time at different depths in a (Chromosol) soil profile irrigated with effluent. This output is typical of that produced by commercially available software (in this case 'the Probe'). In Figure A4.3, a one-hour irrigation was inefficient (little change in θ), with rainfall (30+ mm) causing water movement through the soil profile to a depth 1.0 m. For irrigation scheduling and management it is common to display this information, which is needed for decision making.

Figure A4.3.

FIGURE A4.3. Measurement of soil water content with time during an irrigation cycle in an effluent-irrigated eucalypt plantation.
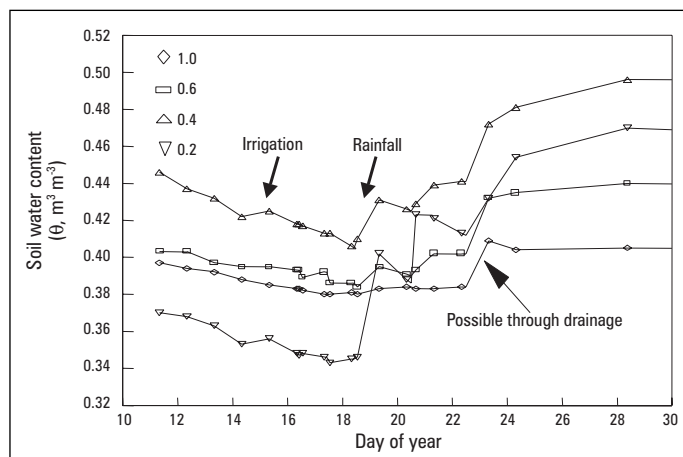
Potential limitations

POTENTIAL LIMITATIONS

A disadvantage of the NMM technique is the radioactive source. In NSW and other Australian States a licence is required to own, operate and store a neutron meter. Gee *et al*. (1976) reported the radiation hazards associated with neutron fluxes in two neutron meters, each with an activity of 100 mCu. They indicated that safe operation incorporated an awareness of the time spent close to the source (that is, carrying the meter) and of neutron escape through the soil surface.

Neutron meters with differing activities (commonly between 10 and 100 mCu) are commercially available. The activity needs to be considered with respect to the radiation hazard, but, as shown by van Bavel *et al*. (1961) and Haverkamp *et al.* (1984), higher source activities will yield lower variation in recorded neutron counts. An alternative action is to increase the count time of the meter, although economically this is often difficult to justify.

Another concern about widespread and continued use of NMM technology is the time taken for readings. As shown in Table A4.1, the increasing count-time improves confidence in the recorded soil water content through improving the instrument precision. However, the longer count time also obviously increases the total time for measurement—always a concern in the current budgeting parameters we operate in. Field staff often have to collect readings in adverse conditions, and other occupational health and safety factors may require some consideration.

Finally, the need for calibration is a limitation of the NMM technique, as with most (currently all!) soil-water-measurement procedures. In general, with irrigation the need for calibration is reduced because managers (farmers) can improve the efficiencies of other components of the irrigation system. For example, in surface irrigation,

large amounts of water (1+ ML ha^{-1}) are added with each irrigation. A 5% calibration error in the determination of soil water content will not greatly alter the manager's decision of when to irrigate, given the ordering time, delivery time and volume of water applied. However, in scientific studies we are interested in minimising error, so calibration of some form is required. The argument about what parameters should be considered continues. Ideally, for given soil types and conditions (for example, a range of bulk densities) calibrations should be available and used. No single database is available for this purpose, and site calibration is recommended in long-term and significant research applications.

Maintenance

MAINTENANCE

The maintenance of neutron moisture meters is instrument dependent. Considerable progress in the past forty-five years has improved the instrument stability, and the NMM is now considered a robust field instrument. As with all scientific equipment, care should be taken to minimise contact with moisture (corrosion is accelerated in enclosed, wet storage cases because of the high relative humidity) and dust. Also, the detector tubes are not known to survive 'bouncing' at the bottom of access tubes. Take care when you are lowering the sensor down the tubes.

If you are using an NMM with a nicad-based battery it is strongly recommended that you cycle the battery charge. To do this, fully charge the batteries and then take the readings. When the 'low battery' signal lights up and the readings are complete, either continually download (transfer data to the computer) from the probe till the batteries are flat, or take extended readings (of no value so as not to lose information). Then fully charge the instrument before doing more readings. If the nicad batteries are continually charged, their effective life is reduced and the time between recharging will decrease, leading to shorter time-periods for data collection and storage. If the data are stored on the NMM and transferred to the PC, this process should be done with the NMM connected to the instrument charger to ensure that the batteries do not go flat during data transfer.

Stopper the tubes at the bottom to minimise water ingress, and cover them at the top. An aluminium can is ideal, although inquisitive animals can remove light aluminium cans. If this happens, put a rubber stopper in the top of the tube and place the aluminum can on top. The tubes should be free from moisture: if condensation occurs, remove it with a rag attached to a length of wire or broom handle.

Positive attributes

POSITIVE ATTRIBUTES

The neutron moderation technique is very robust in operation, and the field technique is well established. A good standard procedure for installation allows rapid deployment of access tubes and relatively straightforward data collection. There are many NMM instruments in use in Australia for agriculture and other enterprises. Calibration equations for many soils have already been developed (for example, O'Leary and Incerti 1993, McKenzie *et al.* 1990, Jayawardane *et al.* 1983), and this background information should be useful.

The neutron technique measures a large volume of soil, compared with dielectric techniques in particular. The ability to integrate readings from a large volume of soil is a positive aspect of the technique, as it takes into account variations in the soil. In duplex soil, or where there is a sharp wetting front, the large measured volume can, however, lead to difficulty in data interpretation (Williams *et al*. 1981).

The NMM technique is especially suitable for non-intensive, temporally based measurement through the soil profile, particularly at depth (> 2 m). If time costs are minimal, then the use of the NMM is very cost effective once you have bought the equipment. The NMM technique will no doubt continue in widespread use for some years.

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Appendix 5

A Value Selection Method for Choosing Between Alternative Soil Moisture Sensors

(Extract by Jeremy Cape from Land and Water Resources Research and Development Corporation Project No. AIT2, 1997).

This extract outlines a value selection method, based on answering a series of questions for choosing which soil moisture sensor is most applicable to a particular situation.

Table A5.1 details questions to be answered in regard to each attribute you are selecting for. Table A5.2 is a worked example comparing two hypothetical devices, Device A and Device B. It is stressed that a comparison or judgement about devices was not within the scope of this study. Devices A and B are not intended to represent particular devices, merely to demonstrate the value selection methodology.

It is clear that the further adoption of soil water sensing devices is limited by the lack of a universally accepted method of appraisal. In spite of the relative simplicity of the selection method outlined in this paper, there is still scope for people to make their own interpretations and score some attributes incorrectly. This problem would be overcome if a universal test and calibration method for soil water sensors could be developed.

The following steps are used in the evaluation procedure.

1. For each *Yes* or *No* answer score a *one* (1) or *zero* (0) in column B of Table A5.1. In the operation and maintenance section each answer has a value of a quarter (0.25), since there are four answers required.

2. For each attribute multiply the point in column B with the weight in column A to obtain column C. Column C is the relative importance.

3. Total all the numbers in column C to obtain the total relative importance, T.

4. Calculate COST, the total estimated life cost of the sensor, by estimating capital, installation, running and maintenance costs for the expected life of the sensor.

5. Divide COST by LIFE, the expected life of the sensor in years, to determine A, the annual cost of the sensor.

6. A = COST/LIFE

7. Divide the total, T, by the annual cost of the sensor to obtain the value, V, of the sensors.

8. V = T/A

9. The sensor with the lowest value may be more suited to your needs and gives you the best value for money.

Table A5.1.

TABLE A5.1. Evaluation procedure table (Cape 1997).

ATTRIBUTES	WEIGHT (A)	POINT (B)	SCORE (C)
Effective range of measurement	8		
water of interest to you? (Yes =1; No =0)			
Accuracy	14		
Is the sws able to measure all ranges of soil (Yes =1; No =0)			
Soil types (For use with range of soils)	11		
Is the sensor accuracy enough for your purpose? Is the sensor's accuracy affected by the soil type? (Yes = 0; No = 1)			
Reliability	13		
Do you have any personal, other users' or literature-based idea of the reliability of the sensor, and is the failure rate satisfactory to you? (Yes = 1; No = 0)			
Frequency/soil disturbance	8		
Can the sensor provide quick or frequent readings in undisturbed soil? (Yes = 1; No = 0)			
Data handling	8		
Will you have difficulty in reading or interpreting data? (Yes = 0; No = 1)			
Communication (for remote data manipulation)	10		
Does the sensor provide data logging and downloading capabilities and friendly software for analysing and interpreting the data? (Yes = 1; No = 0)			
Operation and maintenance	10		
Is the sensor calibration universal? Does the sws have a long life (> 5 years)? Is the sensor maintenance free? Is the sensor easy to install? Give the sensor ¼ for each Yes answer. Total:			
Safety	8		
Does use of the sensor entail any danger? (Yes = 0; No = 1)			
Total (T)			

Table A5.2.

TABLE A5.2. Evaluation procedure example.

ATTRIBUTES	Weight (A)	DEVICE A		DEVICE B	
		Point (B) (B)	Score (C) (C)	Point (B) (B)	Score (C) (C)
Effective range of measurement	**8**				
Is the sws able to measure all ranges soil water of interest to you? (Yes =1; No = 0)		0	0	1	8
Accuracy	**14**				
Is the sensor accuracy enough for your purpose? (Yes = 1; No = 0)		0	0	1	14
Soil types (For use with range of soils)	**11**				
Is the sensor's accuracy affected by the soil type? (Yes = 0; No = 1)		1	11	0	0
Reliability	**13**				
Do you have any personal, other users' or literature-based idea of the reliability of the sensor, and is the failure rate satisfactory to you? (Yes =1; No = 0)		0	0	1	13
Frequency/soil disturbance	**8**				
Can the sensor provide quick or frequent readings in undisturbed soil? (Yes = 1; No = 0)		1	8	0	0
Data handling	**8**				
Will you have difficulty reading or interpreting data? (Yes = 0; No = 1)		1	8	1	8
Communication (for remote data manipulation)	**10**				
Does the sensor provide data logging and downloading capabilities and friendly software for analysing and interpreting the data? (Yes = 1; No = 0)		0	0	1	10
Operation and maintenance	**10**				
Is the sensor calibration universal?		¼	7.5	¼	5
Has the sws got long life (> 5 years)?		¼		0	
Is the sensor maintenance free?		0		¼	
Is the sensor easy to install?		¼		0	
Give the sensor ¼ for each Yes answer. Total		¾		½	
Safety	**8**				
Does use of the sensor entail any danger? (Yes = 0; No = 1)		1	8	0	0
Total (T)			**42.5**		**58**

Reference
Cape, J. 1997. *A Value Selection Method for Choosing Between Alternative Soil Moisture Sensors Project No. AIT2*, Land and Water Resources Research and Development Corporation Report

Appendix 6

Annual Crop Soil-Moisture-Monitoring Cost Comparison

(by David Williams, NSW Agriculture 1999)

Soil moisture monitoring tool categories (based on features and use)	Configuration for one site on 50 Ha	Data-collection labour cost over a 5-month season @ $20/h for 1 site	Site set-up cost, including installation	Extra equipment cost to be split over seasons	Total cost: first season per site	$/ha 1 year	$/ha 5 years	$/ha 10 years	Data rank *
Category 1: low purchase cost, high labour, user takes readings, fixed depths									
Tensiometer – puncture type	3 units – 3 depths	$300	$125	$800/10	$505	$10.10	$6.82	$6.41	4
		$300	$650	Nil	$950	$19.00	$8.60	$7.30	4
Gypsum blocks	3 blocks – 3 depths	$250	$85	$600/10	$395	$7.90	$5.58	$5.29	4
Category 2: low purchase cost, high labour, user takes readings, multi-depth									
Gopher®	1 tube < 12 depths	$200	$40	$1650 / 10 #	$405	$8.10	$4.82	$4.41	3
Sentek Diviner 2000®	1 tube 11 depths	$200	$40	$3200 / 10 #	$560	$11.20	$5.44	$4.72	3
Category 3: low purchase cost, low labour, constant readings, fixed depths									
Netafim soil moisture probe	1 unit – 3 depths	$100	$1200	Nil	$1300	$26	$6.80	$4.40	3

Soil moisture monitoring tool categories (based on features and use)	Configuration for one site on 50 Ha	Data-collection labour cost over a 5-month season @ $20/h for 1 site	Site set-up cost, including installation	Extra equipment cost to be split over seasons	Total cost: first season per site	$/ha 1 year	$/ha 5 years	$/ha 10 years	Data rank *
Category 4: high purchase cost, low labour, constant readings, multi depth									
Sentek Enviroscan®	1 tube – 4 depths	$100	$1500	$1500/8	$1790	$35.80	$8.75	$5.38	1
C-Probe®	1 tube – 4 depths	Nil	$1300	$3300 5 km	$1630	$32.60	$6.52	$3.26	1
				$8100 40 km #	$2110	$42.20	$8.44	$4.22	
Category 5: high purchase cost, high labour, user takes readings, multi depth									
Neutron probe – contractor	3 averaged tubes	Contractor	$1100	Contractor	$1100	$22	$22	$22	2
– second hand	1 tube only	$300	$40	$7000/10 #	$1040	$20.80	$9.60	$8.20	3
– new	3 averaged tubes	$400	$120	$12000/10 #	$1720	$34.40	$15.20	$12.80	2
– new with 50 sites	3 averaged tubes	$400	$120	$12000/50	$760	$15.20	$11.36	$10.88	2

* Data rank is related to how comprehensive the data is, ranging between 1 (high) and 4 (low).

would be more economic over more sites, that is 20 to 50 sites

Note:

Costs per ha (based on 1 site per 50-ha field of uniform soil type and crop) without data interpretation, maintenance, int, dep, cpi etc.

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